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(54) **METHOD AND APPARATUS FOR PROCESSING A MICROELETRONIC WORKPIECE INCLUDING AN APPARATUS AND METHOD FOR EXECUTING A PROCESSING STEP AT AN ELEVATED TEMPERATURE**

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Publication Classification

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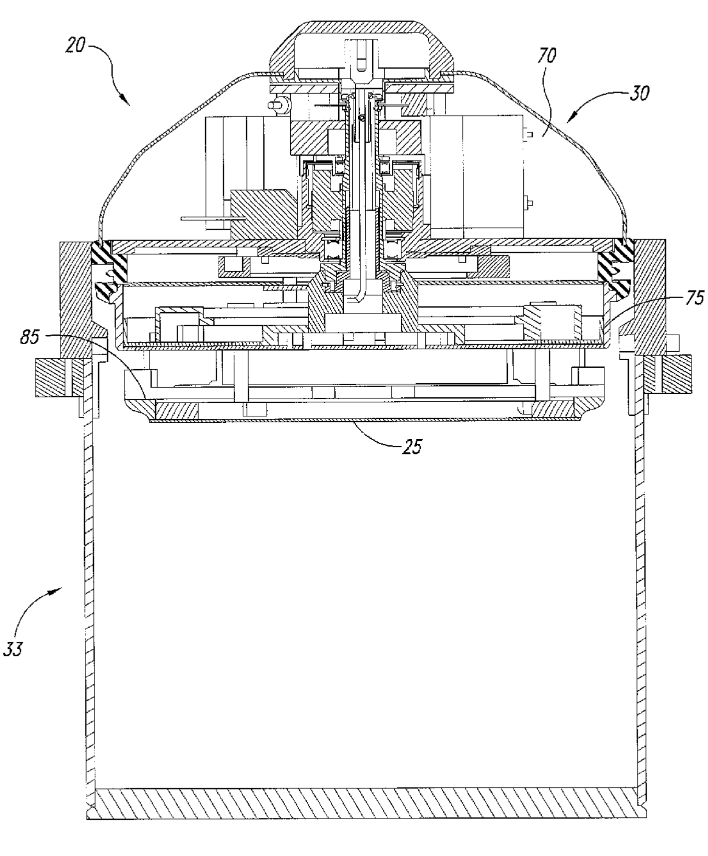
(52) **U.S. Cl.** **266/81**; 266/250

(57) **ABSTRACT**

An apparatus for thermally processing a microelectronic workpiece is set forth. The apparatus comprises a first assembly and a second assembly, disposed opposite one another, with an actuator disposed to provide relative movement between the first assembly and second assembly. More particularly, the actuator provides relative movement between at least a loading position in which the first assembly is in a state for loading or unloading of the microelectronic workpiece, and a thermal processing position in which the first assembly and second assembly are proximate one another and form a thermal processing chamber. A thermal transfer unit is disposed in the second assembly and has a workpiece support surface that is heated and cooled in a controlled manner. As the first assembly and second assembly are driven to the thermal processing position by the actuator, an arrangement of elements bring a surface of the microelectronic workpiece into direct physical contact with the workpiece support surface of the thermal transfer unit. In a preferred embodiment, the thermal transfer unit is comprised of a low thermal mass heater and a high thermal mass cooler disposed to controllably cool the low thermal mass heater.



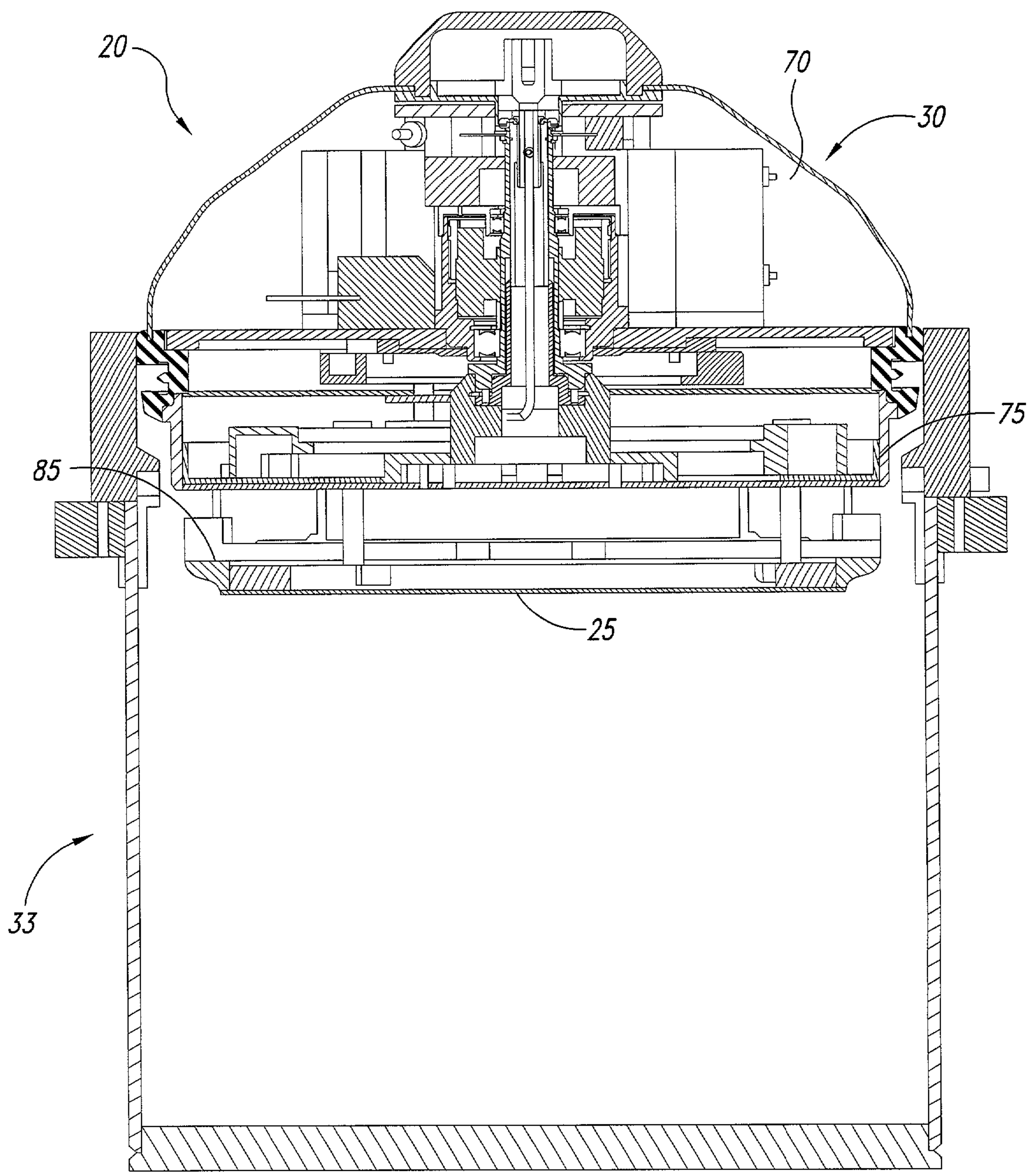
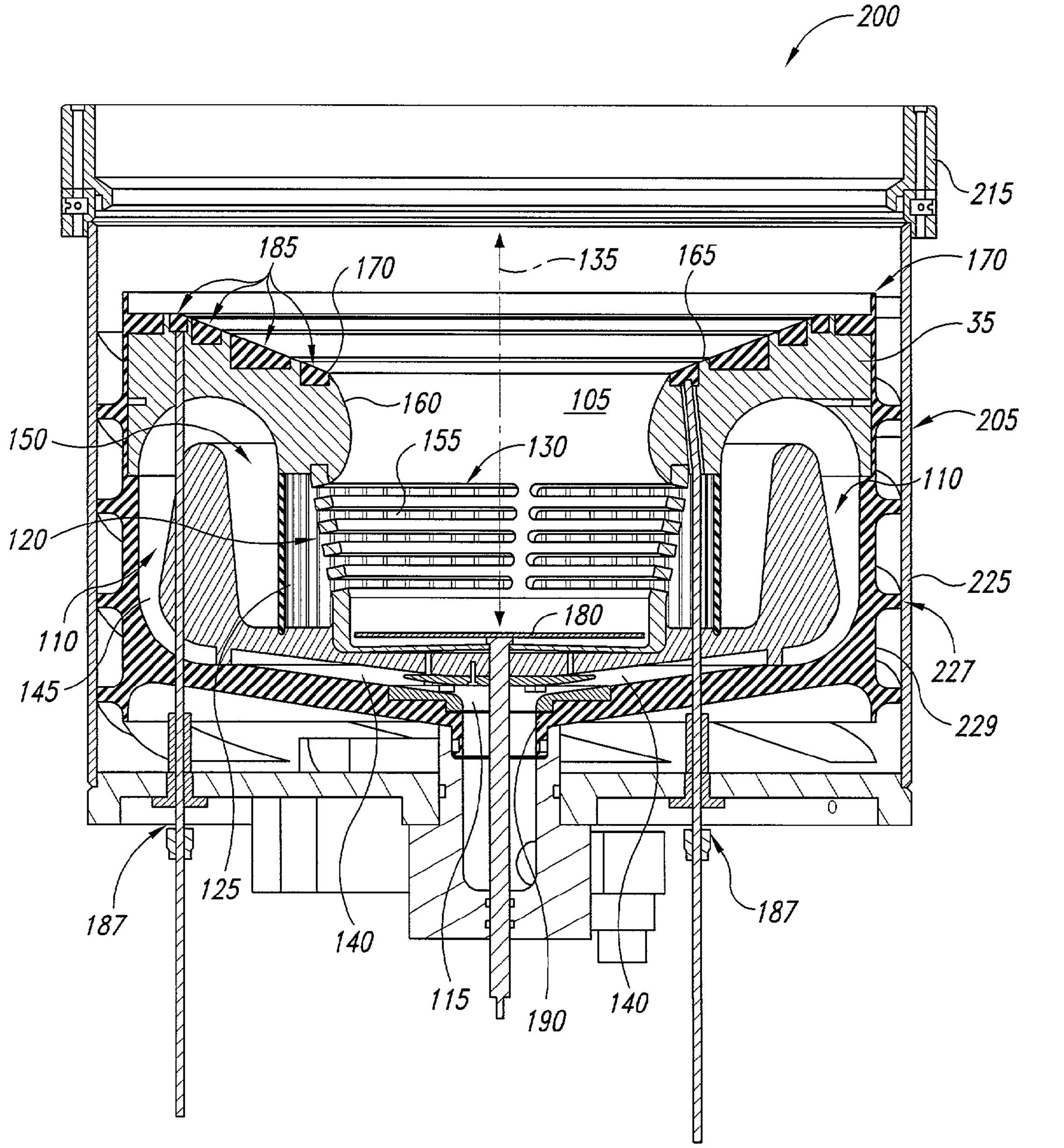


Fig. 1A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145
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125
187
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115
190
140

Fig. 1B

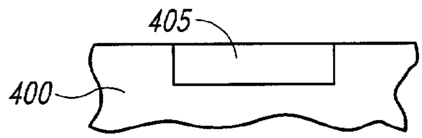

Fig. 2A

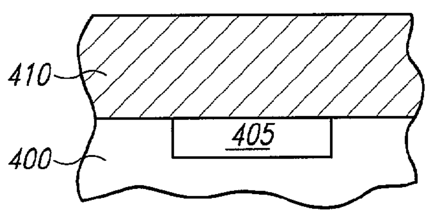

Fig. 2B

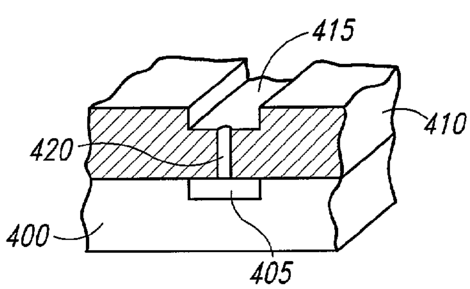

Fig. 2C

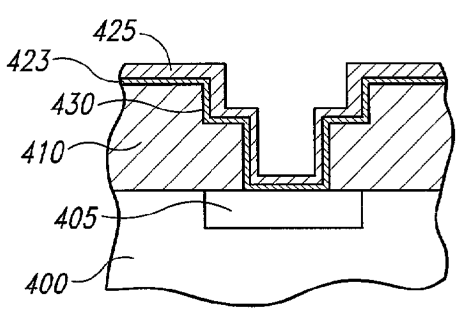

Fig. 2D

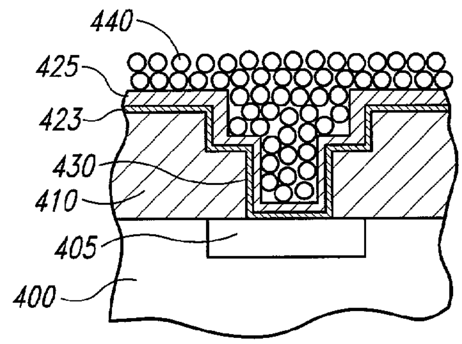

Fig. 2E

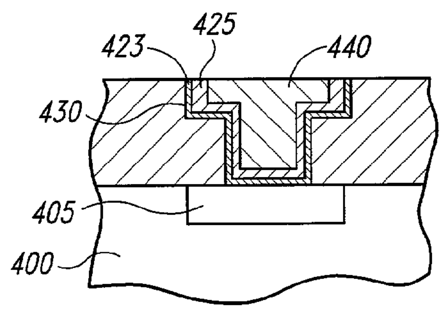

Fig. 2F

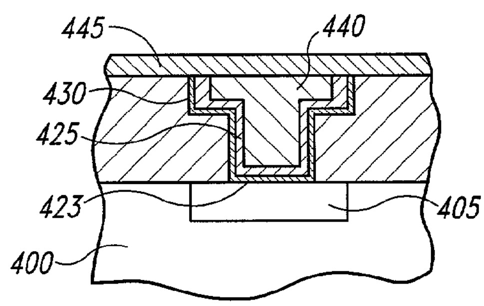

Fig. 2G

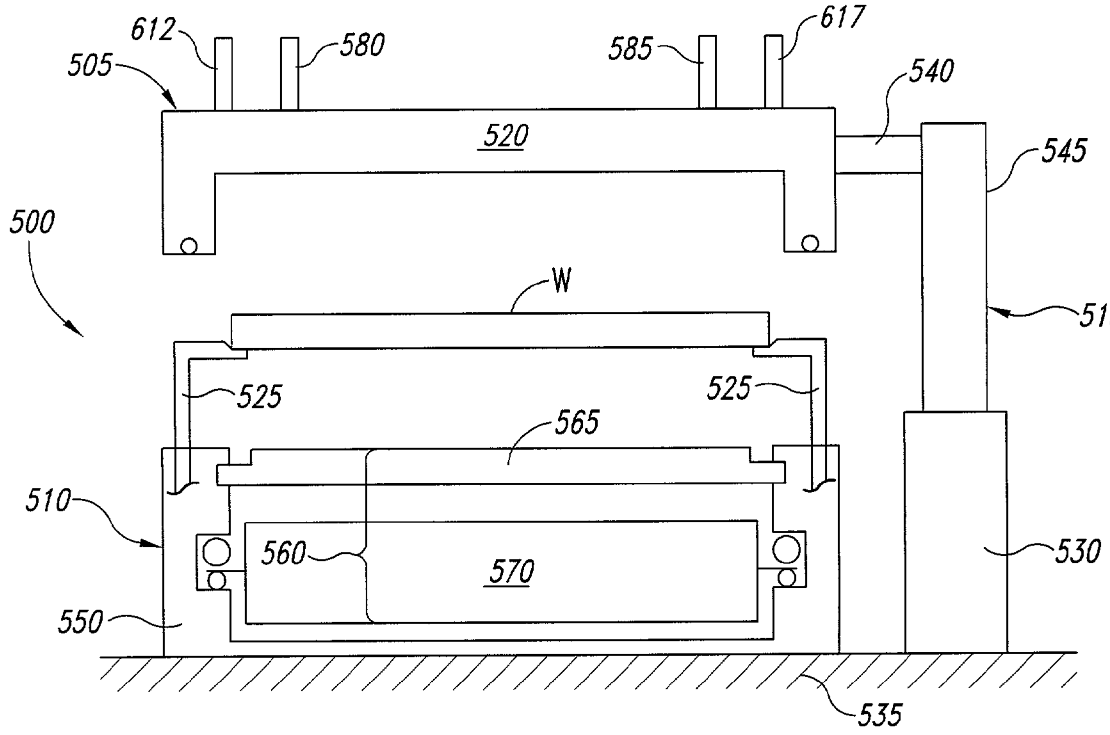
612
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Fig. 3A

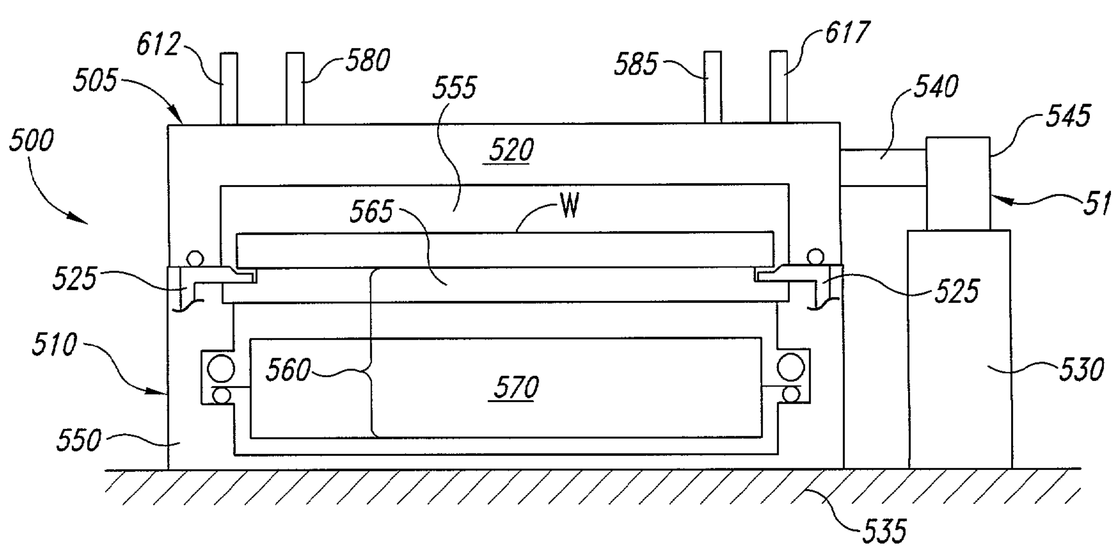
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Fig. 3B

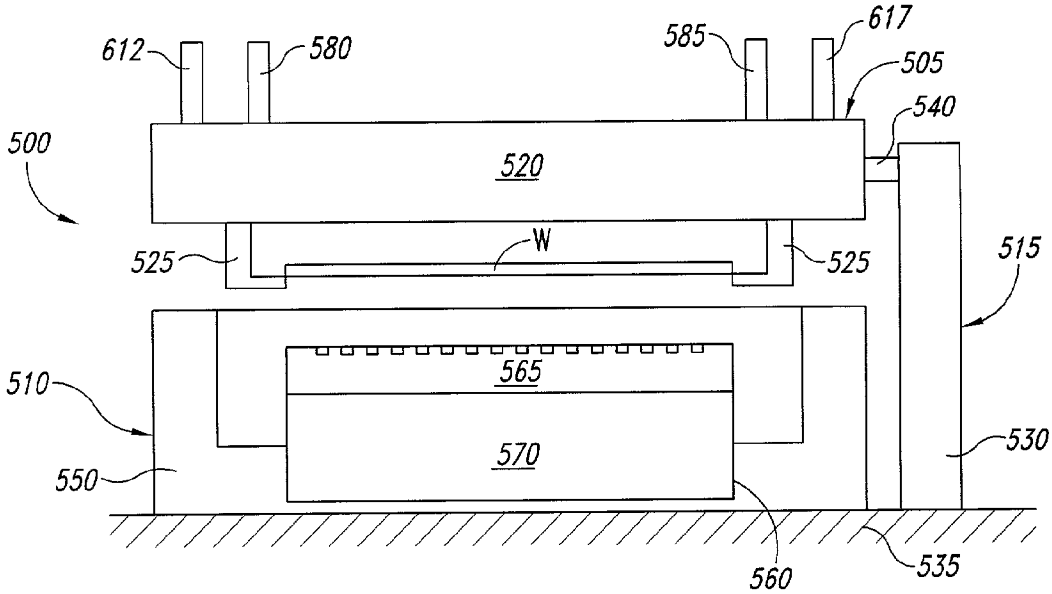
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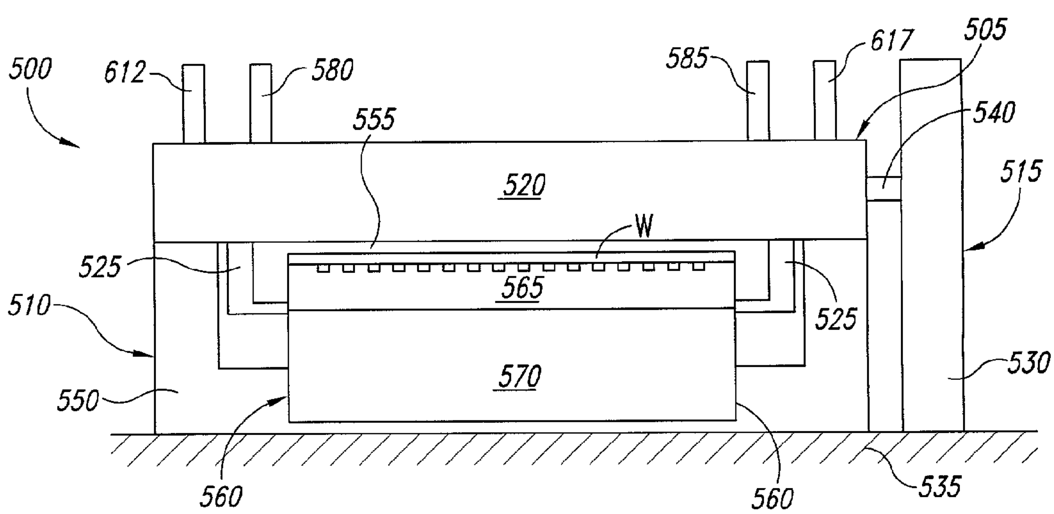
Fig. 3C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580
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560
535

Fig. 3D

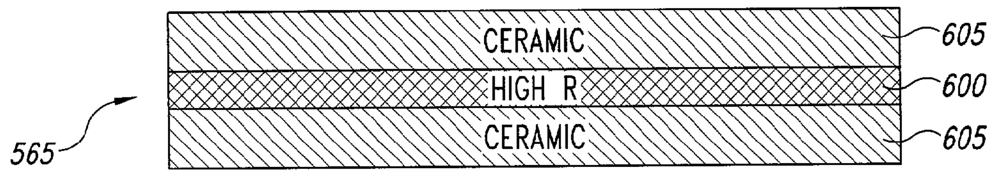


Fig. 4A

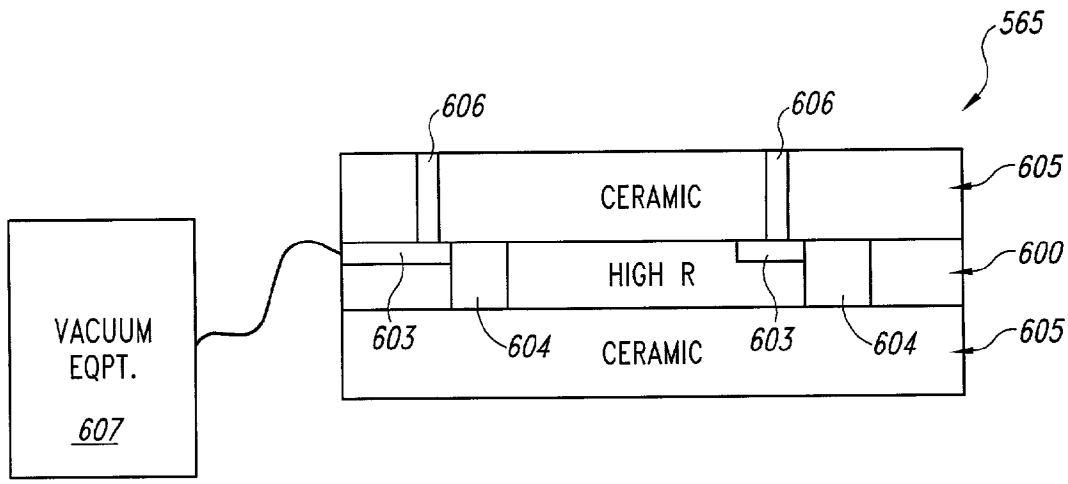


Fig. 4B

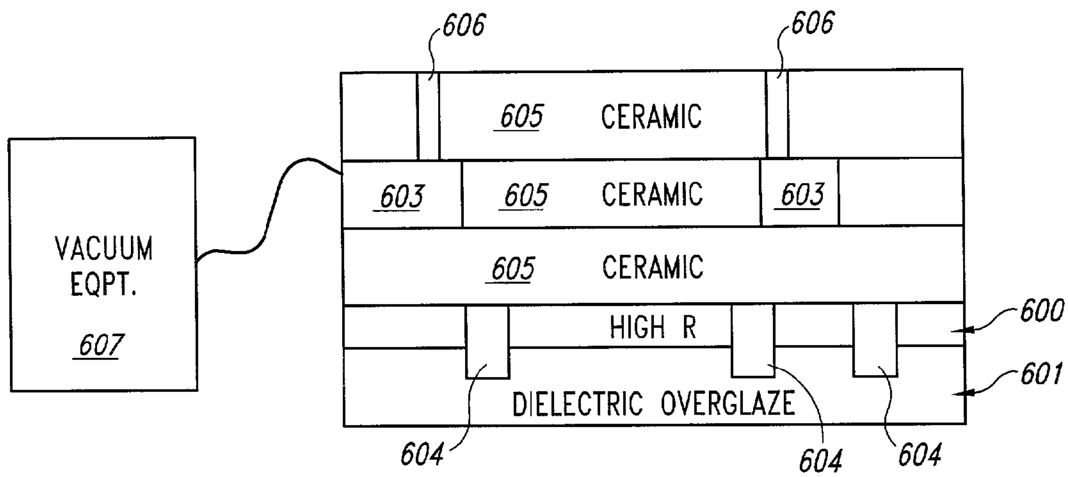


Fig. 4C

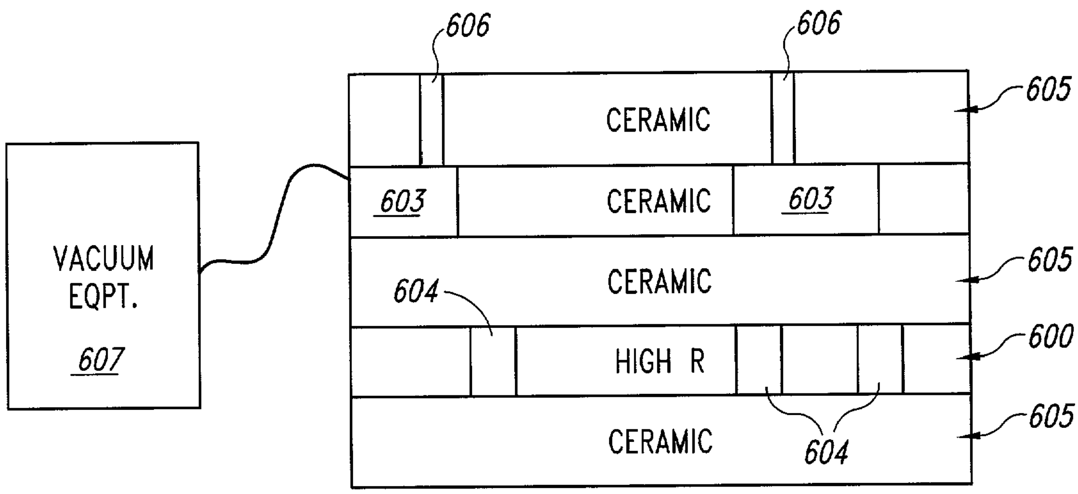
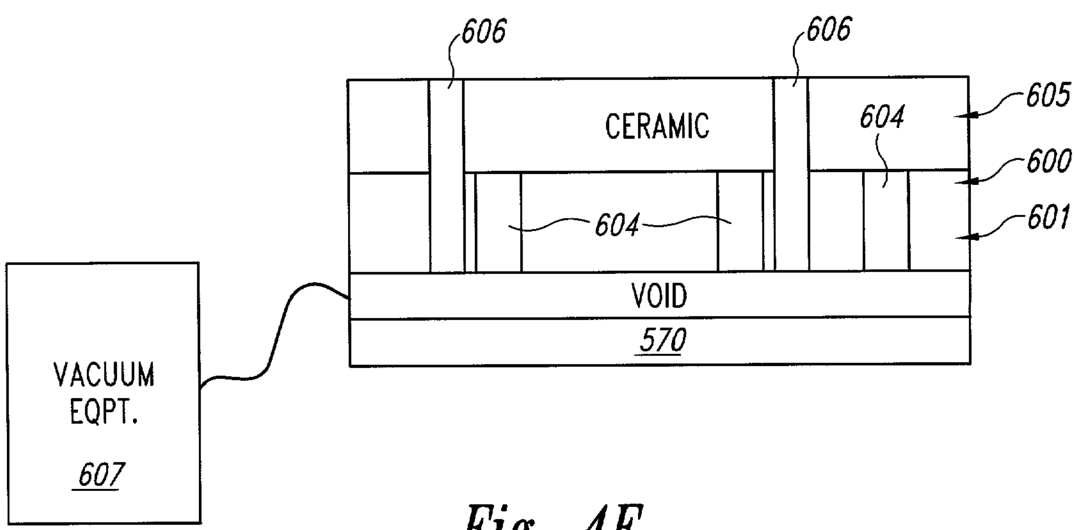

606
606
605
CERAMIC
603
CERAMIC
603
VACUUM EQPT.
607
CERAMIC
605
604
HIGH R
600
CERAMIC
604
605

Fig. 4D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CERAMIC
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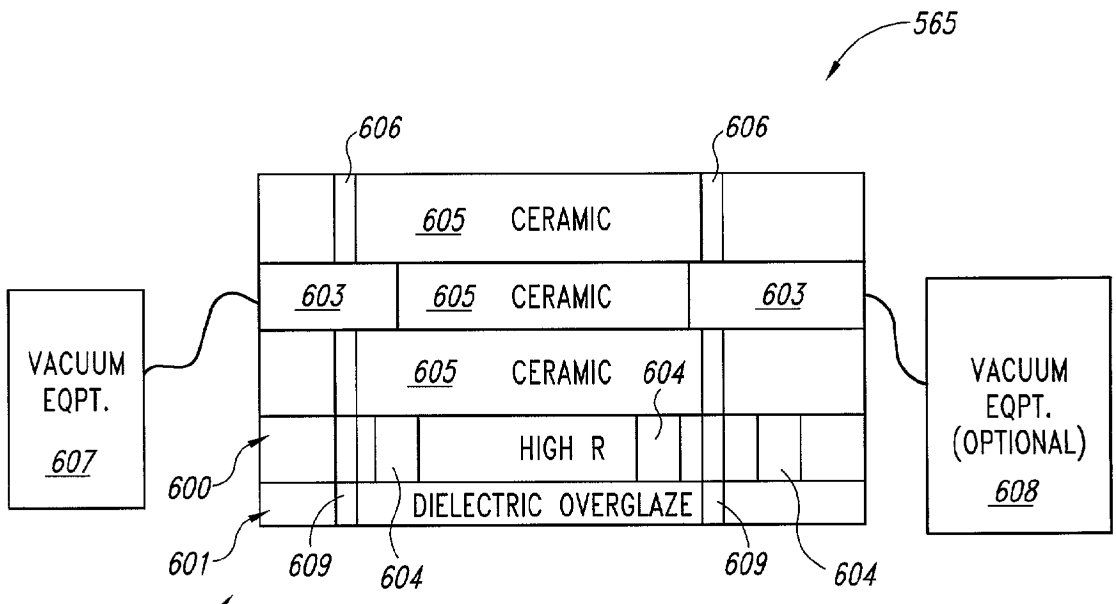
600
604
601
VOID
570
VACUUM EQPT.
607

Fig. 4E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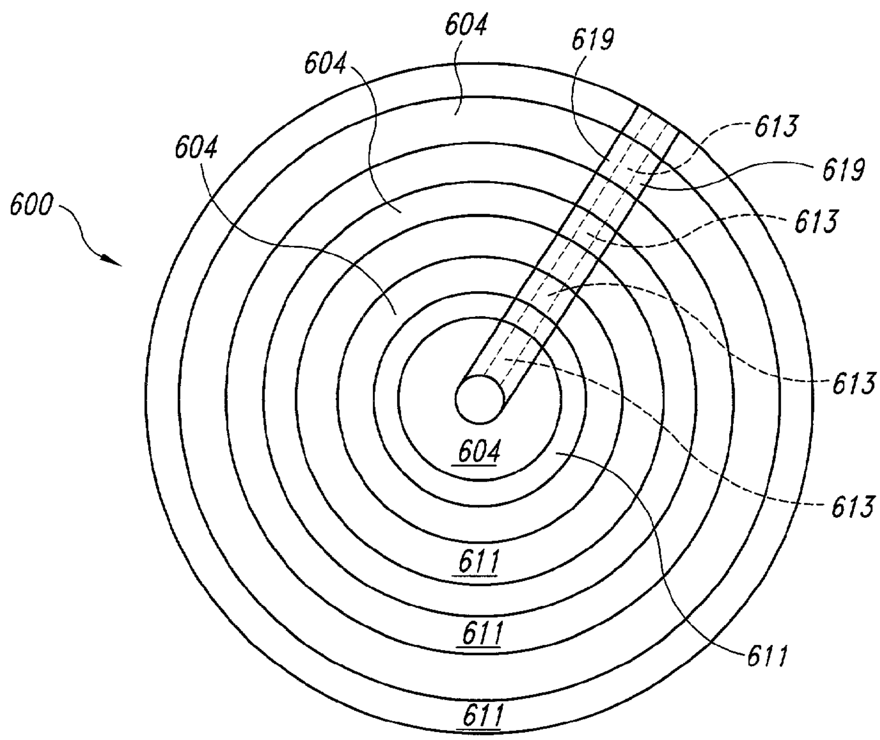
606
606
605 CERAMIC
603
605 CERAMIC
603
VACUUM EQPT. 607
605 CERAMIC 604
VACUUM EQPT. (OPTIONAL) 608
HIGH R
600
DIELECTRIC OVERGLAZE
601
609
604
609
604
565

Fig. 4F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611

Fig. 4G

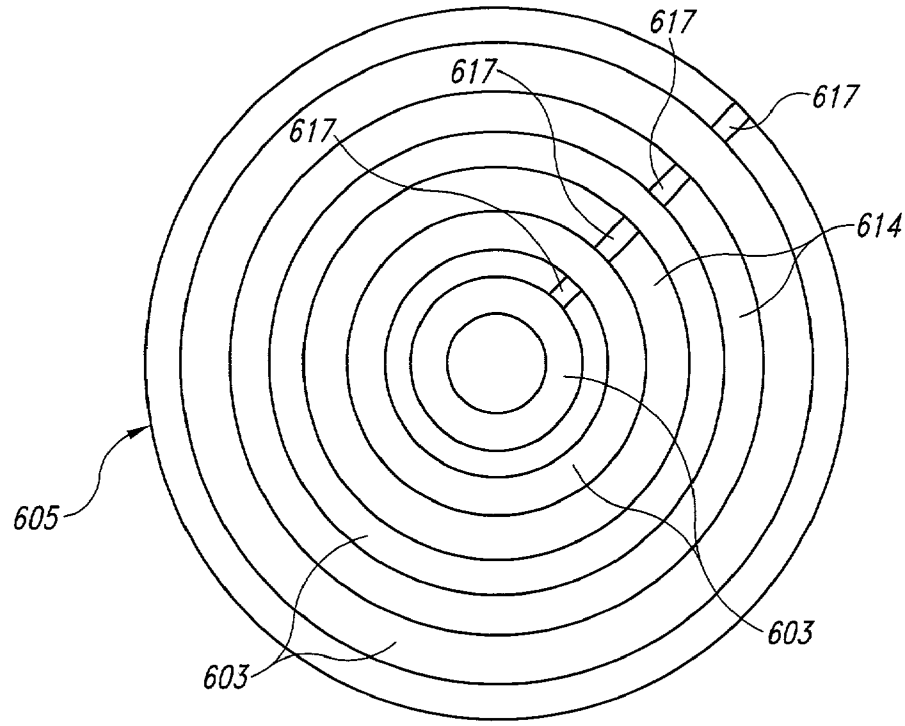


Fig. 4H

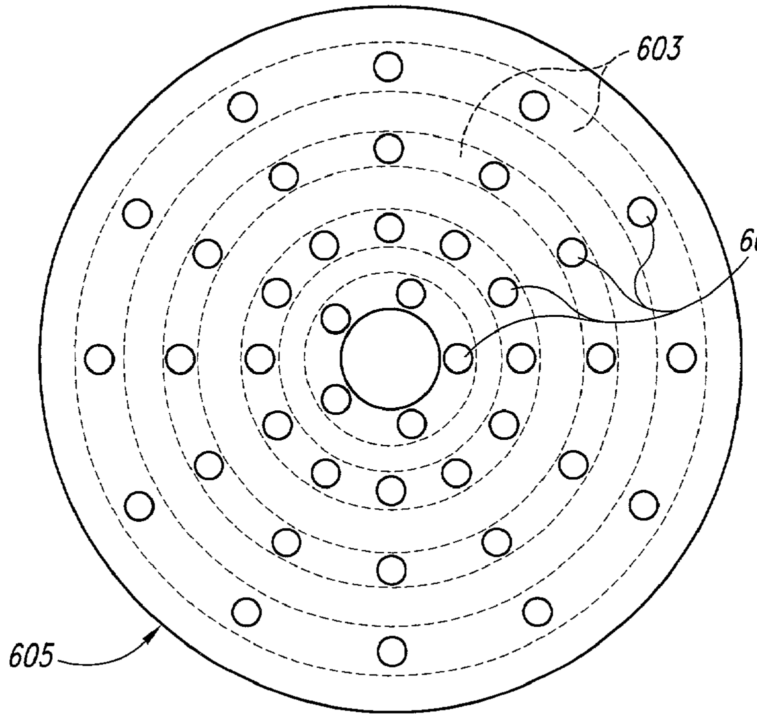


Fig. 4I

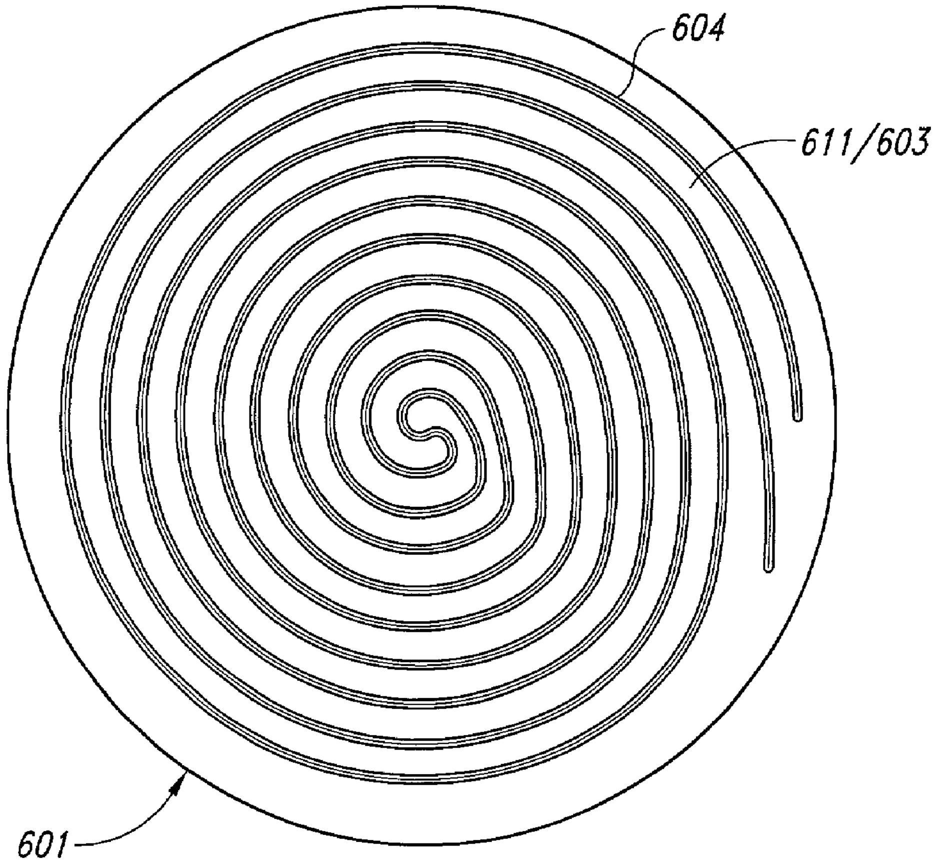


Fig. 4J

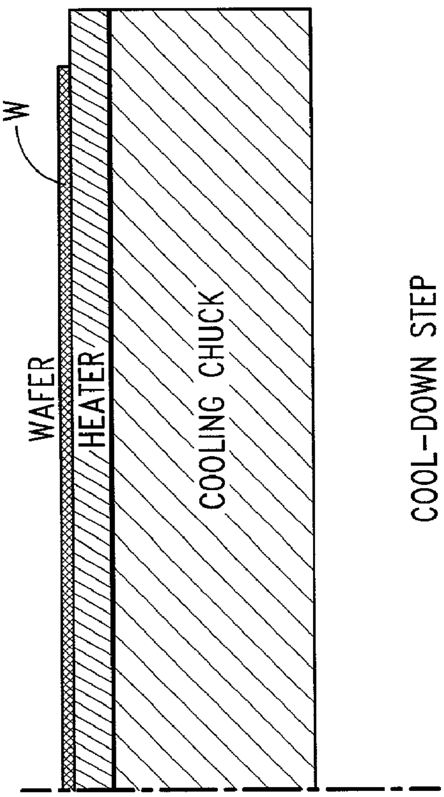

W
WAFER
HEATER
COOLING CHUCK
COOL-DOWN STEP

Fig. 5B

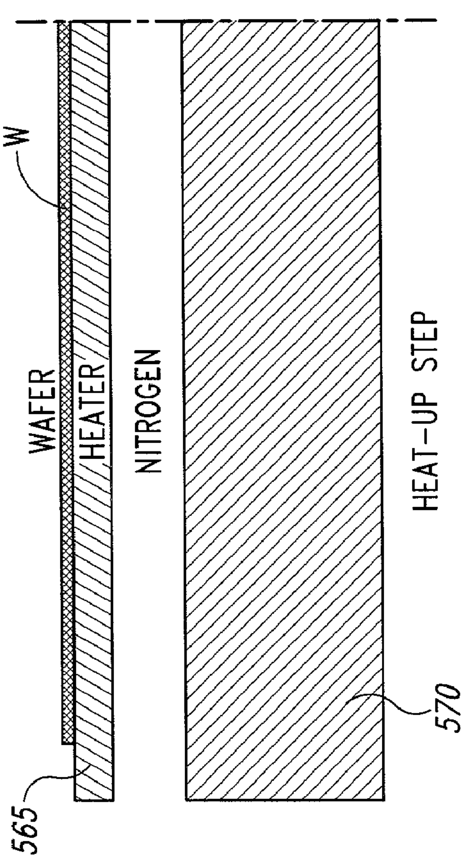

W
WAFER
HEATER
NITROGEN
HEAT-UP STEP
570
565

Fig. 5A

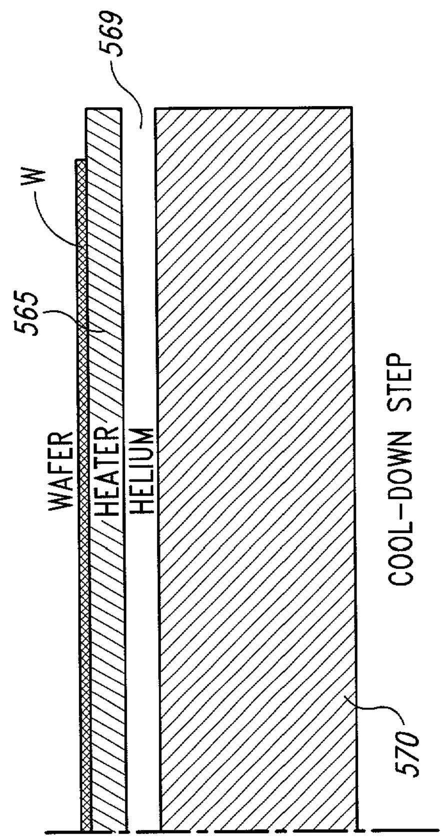

569
W
565
WAFER
HEATER
HELIUM
COOL-DOWN STEP
570

Fig. 6B

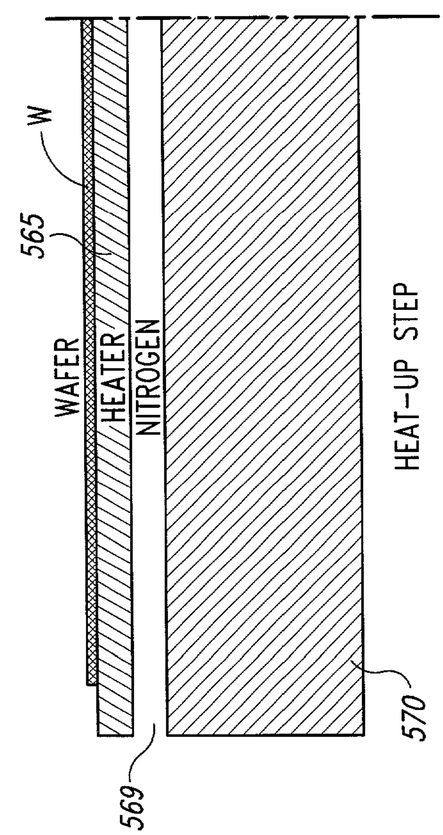
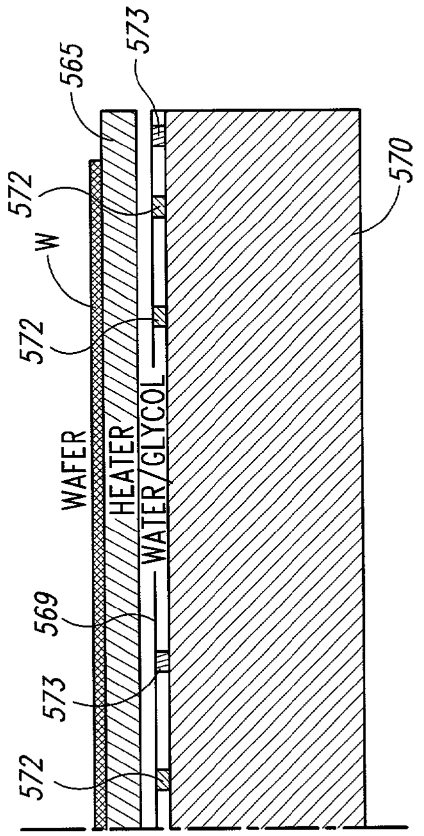

W
565
WAFER
HEATER
NITROGEN
HEAT-UP STEP
570
569

Fig. 6A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573
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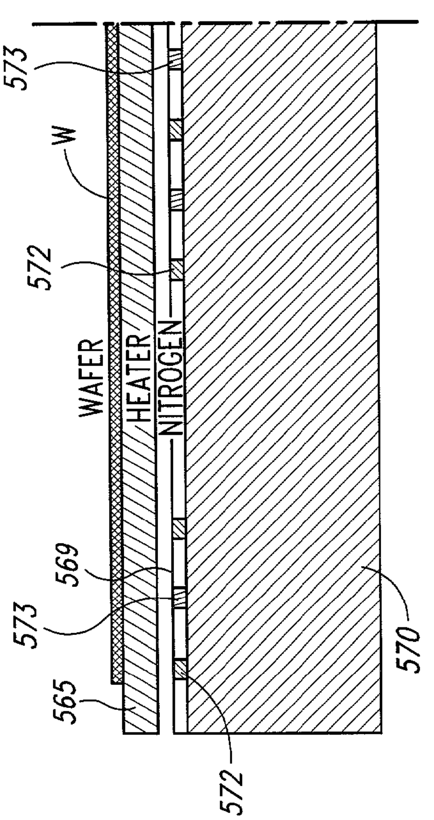
W
572
570
WAFER
HEATER
WATER/GLYCOL
569
573
572

Fig. 7B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WAFER
HEATER
NITROGEN
569
573
565
570
572

Fig. 7A

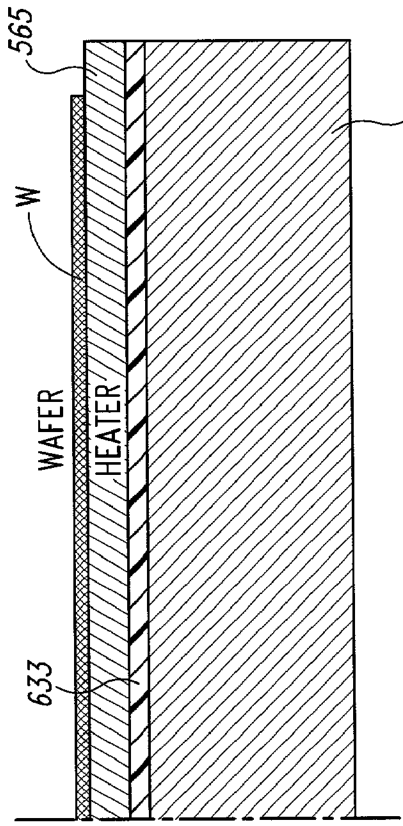

565
570
W
WAFER
HEATER
633

Fig. 8B

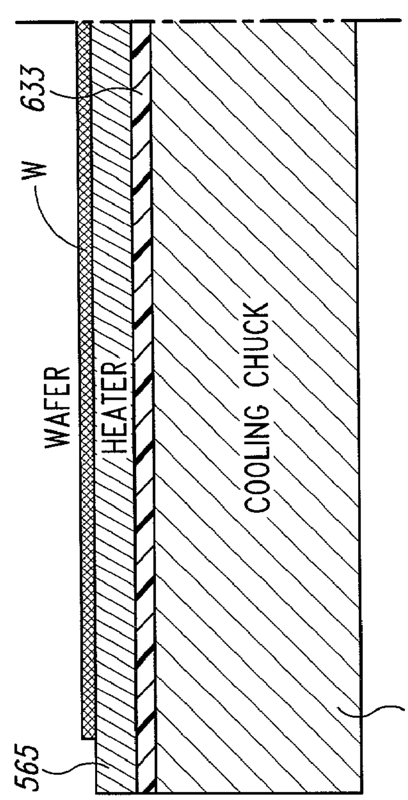
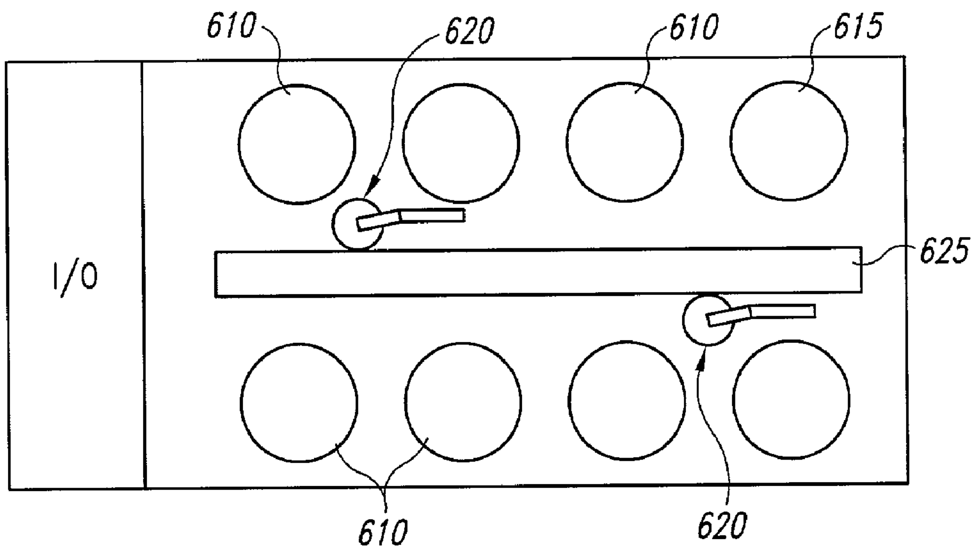

633
W
WAFER
HEATER
COOLING CHUCK
570
565

Fig. 8A


610
620
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615
I/O
625
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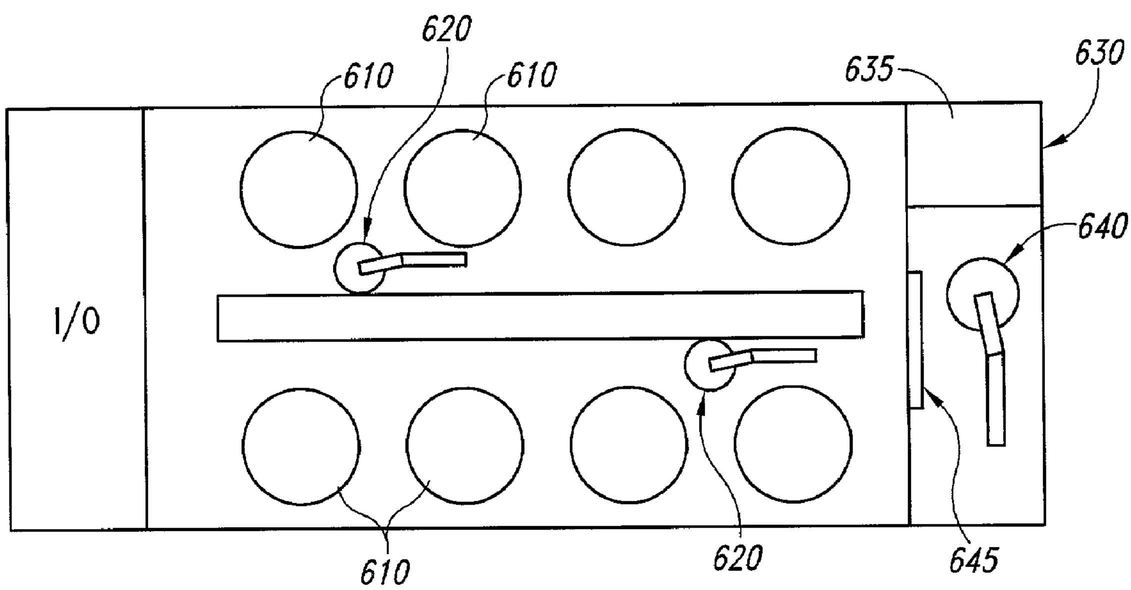
620

Fig. 9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630
I/O
640
610
620
645

Fig. 10

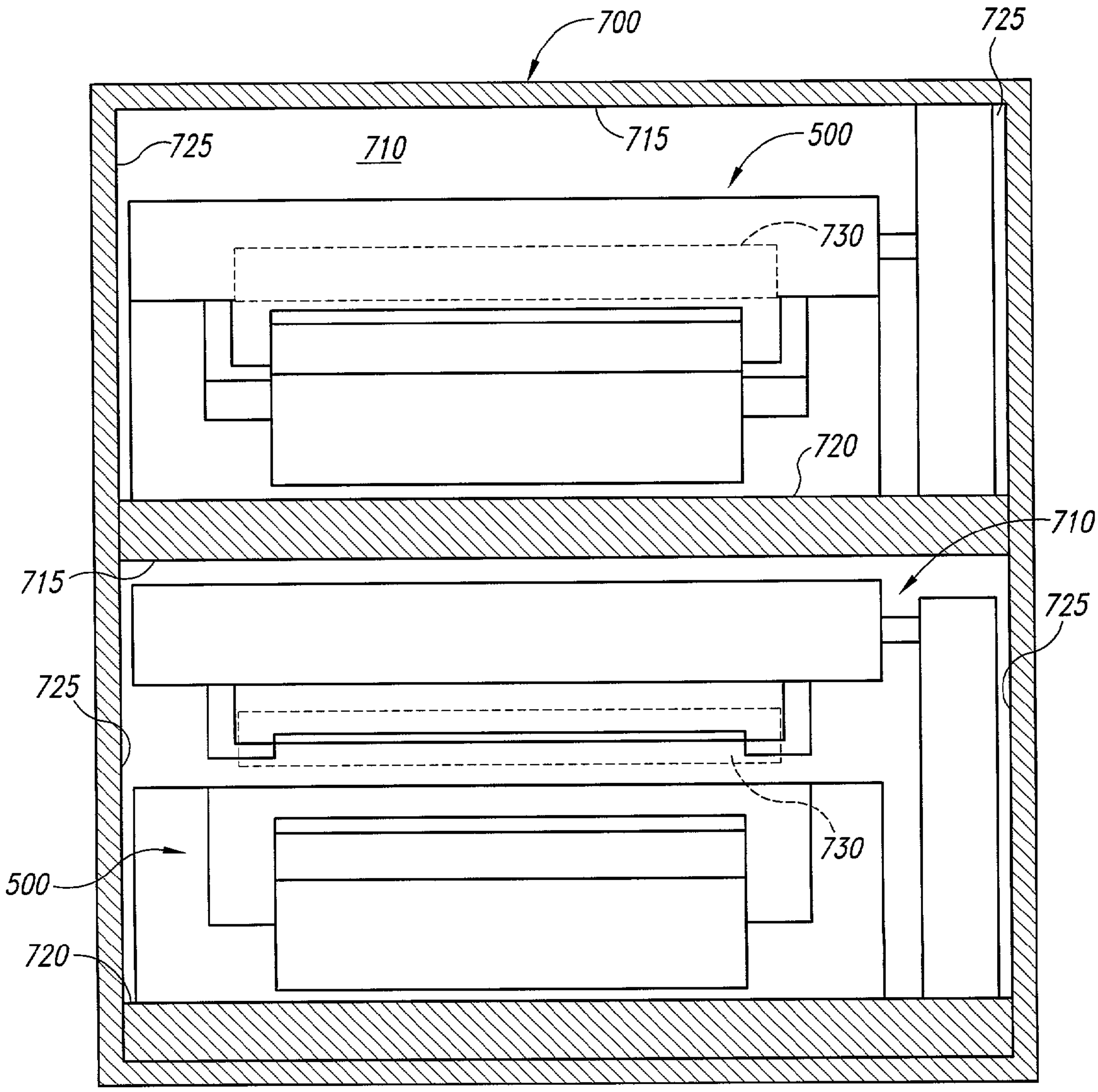

Fig. 11

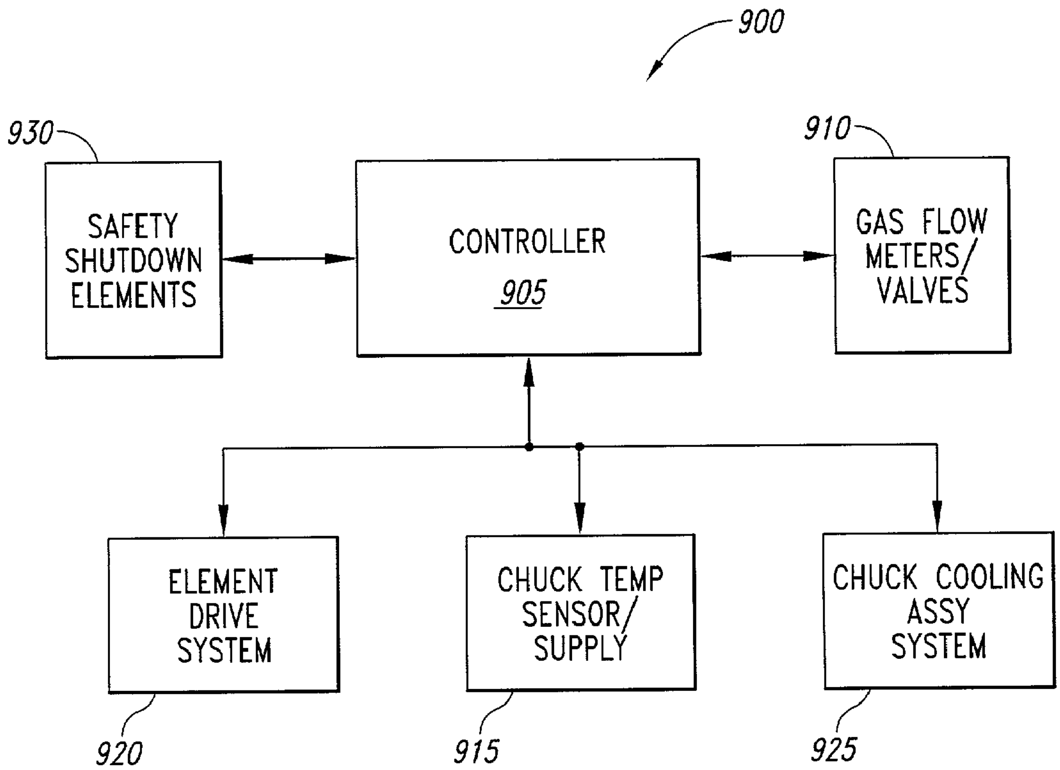
900
930
SAFETY SHUTDOWN ELEMENTS
CONTROLLER
905
910
GAS FLOW METERS/ VALVES
ELEMENT DRIVE SYSTEM
CHUCK TEMP SENSOR/ SUPPLY
CHUCK COOLING ASSY SYSTEM
920
915
925

Fig. 12

METHOD AND APPARATUS FOR PROCESSING A MICROELETRONIC WORKPIECE INCLUDING AN APPARATUS AND METHOD FOR EXECUTING A PROCESSING STEP AT AN ELEVATED TEMPERATURE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not Applicable

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not Applicable

BACKGROUND OF THE INVENTION

[0003] The present invention is generally directed to the processing of a microelectronic workpiece. More particularly, the present invention includes a method and apparatus for processing a microelectronic workpiece at an elevated temperature.

[0004] For purposes of the present application, a microelectronic workpiece is defined to include a workpiece formed from a substrate upon which microelectronic circuits or components, data storage elements or layers, and/or micro-mechanical elements are formed. Although the present invention is applicable to this wide range of products, the invention will be particularly described in connection with its use in the production of interconnect structures formed during the production of integrated circuits on a semiconductor wafer. Still further, although the invention is applicable for use in connection with a wide range of metal and metal alloys as well as in connection with a wide range of elevated temperature processes, the invention will be particularly described in connection with annealing of electroplated copper and copper alloys.

[0005] In the production of semiconductor integrated circuits and other microelectronic articles from microelectronic workpieces, such as semiconductor wafers, it is often necessary to provide multiple metal layers on a substrate to serve as interconnect metallization that electrically connects the various devices on the integrated circuit to one another. Traditionally, aluminum has been used for such interconnects, however, it is now recognized that copper metallization may be preferable. Copper interconnects can help alleviate many of the problems experienced in connection with the current aluminum technology.

[0006] The microelectronic fabrication industry has sought to use copper as the interconnect metallization by using a damascene and/or patterned plating electroplating process where holes, more commonly called vias, trenches and other recesses are used to produce the desired copper patterns. In the damascene process, the wafer is first provided with a metallic seed layer and barrier/adhesion layer that are disposed over a dielectric layer into which trenches are formed. The seed layer is used to conduct electrical current during a subsequent metal electroplating step. Preferably, the seed layer is a very thin layer of metal that can be applied using one of several processes. For example, the seed layer of metal can be laid down using physical vapor deposition or chemical vapor deposition processes to produce a layer on the order of 1000 angstroms thick. The seed layer can also be formed of copper, gold, nickel, palladium, and most or all other metals. The seed layer is formed over a surface that is convoluted by the presence of the trenches, or other device features, which are recessed into the dielectric substrate.

[0007] In single damascene processes using electroplating, a process employing two electroplating operations is generally employed. First, a copper layer is electroplated onto the seed layer in the form of a blanket layer. The blanket layer is plated to an extent which forms an overlying layer, with the goal of completely providing a copper layer that fills the trenches that are used to form the horizontal interconnect wiring in the dielectric layer. The first blanket layer is then subject, for example, to a chemical mechanical polish step in which the portions of the layer extending above the trenches are removed, leaving only the trenches filled with copper. A further dielectric layer is then provided to cover the wafer surface and recessed vias are formed in the further dielectric layer. The recessed vias are disposed to overlie certain of the filled trenches. A further seed layer is applied and a further electroplated copper blanket layer are provided that extend over the surface of the further dielectric layer and fills the vias. Again, copper extending above the level of the vias is removed using, for example, chemical mechanical polishing techniques. The vias thus provide a vertical connection between the original horizontal interconnect layer and a subsequently applied horizontal interconnect layer. Electrochemical deposition of copper films has thus become an important process step in the manufacturing of high-performance microelectronic products.

[0008] Alternatively, the trenches and vias may be etched in the dielectric at the same time in what is commonly called a "dual damascene" process. These features are then processed, as above, with barrier layer, seed layer and fill/blanket layer that fill the trenches and vias disposed at the bottoms of the trenches at the same time. The excess material is then polished, as above, to produce inlaid conductors.

[0009] The mechanical properties of the copper metallization can be quite important as the metal structures are formed. This is particularly true in connection with the impact of the mechanical properties of the copper metallization during chemical mechanical polishing. Wafer-to-wafer and within wafer grain size variability in the copper film can adversely affect the polish rate of the chemical mechanical processing as well as the ultimate uniformity of the surfaces of the polished copper structures. Large grain size and low variations in grain size in the copper film are very desirable.

[0010] The electrical properties of the copper metallization are also important to the performance of the associated microelectronic device. Such devices may fail if the copper metallization exhibits excessive electromigration that ultimately results in an open or short circuit condition in one or more of the metallization structures. One factor that has a very large influence on the electromigration resistance of sub-micron metal lines is the grain size of the deposited metal. This is because grain boundary migration occurs with a much lower activation energy than trans-granular migration.

[0011] To achieve the desired electrical characteristics for the copper metallization, the grain structure of each deposited blanket layer is altered through an annealing process. This annealing process is traditionally thought to require the performance of a separate processing step at which the semiconductor wafer is subject to an elevated temperature of about 400 degrees Celsius. The relatively few annealing apparatus that are presently available are generally stand-alone batch units that are often designed for batch processing of wafers disposed in wafer boats.

[0012] The present inventors have recognized substantial improvements over the foregoing processes and apparatus currently suitable for annealing of metal microstructures. To this end, they have developed an improved annealing apparatus that may be readily integrated into a processing tool incorporating a number of other processing reactors, including, for example, an electroplating reactor.

BRIEF SUMMARY OF THE INVENTION

[0013] An apparatus for thermally processing a microelectronic workpiece is set forth. The apparatus comprises a first assembly and a second assembly, disposed opposite one another, with an actuator disposed to provide relative movement between the first assembly and second assembly. More particularly, the actuator provides relative movement between at least a loading position in which the first assembly and second assembly are in a state for loading or unloading of the microelectronic workpiece, and a thermal processing position in which the first assembly and second assembly are proximate one another and form a thermal processing chamber. A thermal transfer unit is disposed in the second assembly and has a workpiece support surface that is heated and cooled in a controlled manner. As the first assembly and second assembly are driven to the thermal processing position by the actuator, an arrangement of elements bring a surface of the microelectronic workpiece into direct physical contact with the workpiece support surface of the thermal transfer unit.

[0014] In accordance with one aspect of the present invention, the thermal transfer unit comprises a heater having a top surface forming the wafer support surface of the thermal transfer unit, and a bottom surface opposite the top surface. The thermal transfer unit also includes a cooling chuck having a surface proximate the bottom surface of the heater. Various methods and arrangements are set forth to effectively isolate the cooling chuck from the heater during a heating sub-cycle of a complete thermal processing cycle and to conduct heat from the heater to the cooling chuck during a cooling sub-cycle of the thermal processing cycle.

[0015] Another aspect of the present invention relates to the construction of the heater. In accordance with one embodiment, the heater is constructed as a thick film heater that comprises one or more ceramic substrate layers and a layer of high electrical resistance traces, with optional vacuum circuit channels formed in one or more of the layers. The traces of the layer of high electrical resistance traces may be optimized to the shape of the microelectronic workpiece, thereby transferring thermal energy to the microelectronic workpiece in an efficient and uniform manner. The vacuum circuit channels may be ported through the top substrate layer to ensure uniform contact between the workpiece and the top surface of the thick film heater. Further, the vacuum circuit channels may be ported through the lower layer to ensure uniform contact between the heater and the cooling chuck.

[0016] Another aspect of the present invention relates to the use of the thermal reactor at an annealing station of a processing tool. In accordance with one embodiment, the reactor is integrated in the processing tool along with one or more processing stations used to electrochemically deposit a metal layer, such as copper, on the surface of the microelectronic workpiece. In accordance with another embodiment, the reactor is provided in a separate module having its own robotic wafer transfer mechanism. This latter embodiment allows the annealing station to be provided to an end user as an add-on or upgrade.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0017] **FIGS. 1A and 1B** illustrate one embodiment of a plating apparatus that may be used to apply an electrochemically deposited metal layer, such as copper, to the surface of a microelectronic workpiece, such as a semiconductor wafer, the resulting metal layer being suitable for annealing in the thermal reactor of the present invention.

[0018] FIGS. **2A-2G** illustrate the various steps used to deposit a metal in microstructures formed in the surface of a microelectronic workpiece, such metal structures being suitable for annealing in the thermal reactor of the present invention.

[0019] FIGS. **3A-3D** are schematic block diagrams of thermal reactors constructed in accordance with two embodiments of the present invention.

[0020] FIGS. **4A-4F** are a cross-sectional view of four embodiments of a thick film heater that may be used in the thermal transfer unit of the embodiments of the thermal reactor shown in **FIGS. 3A through 3D**.

[0021] FIGS. **4G-4J** are plan views of various elements that form the thick film heater constructions illustrated in FIGS. **4A-4F**.

[0022] FIGS. **5-8** illustrate various manners in which the thick film heater and the cooling chuck may cooperate with one another in the embodiment of the thermal transfer unit.

[0023] **FIGS. 9 and 10** are schematic diagrams of wet chemical processing tool sets that include one or more annealing stations having thermal reactors constructed in accordance with the present invention.

[0024] **FIG. 11** illustrates one manner in which a plurality of thermal reactors of the type shown in **FIGS. 3A through 3D** may be integrated into a single annealing station.

[0025] **FIG. 12** illustrates one embodiment of a programmable control system that may be used to coordinate the operation of the thermal reactor.

DETAILED DESCRIPTION OF THE INVENTION

[0026] The present invention is described here in the context of its use in annealing copper that has been electroplated onto the surface of a microelectronic workpiece. The description in this context is made without limitation of the applicability of the invention to other processes, microelectronic products, or materials. It will be recognized, however, that the application of the disclosed thermal reactor in this context is particularly novel and non-obvious.

[0027] Before a metal layer or structure can be annealed in the thermal reactor of the present invention, the metal layer or structure must first be deposited on the surface of the microelectronic workpiece. In connection with the deposition of copper, the preferred method is electroplating. To this end, **FIG. 1A** shows various components of a processing station suitable for electroplating a metal, such as copper, onto a microelectronic workpiece, such as a semiconductor wafer. It will be recognized, however, that a wide variety of processing station configurations may be used to deposit the metal before it is annealed in the disclosed reactor and that the specific construction of the station is merely exemplary. For example, such a processing station may merely comprise an anode, one or more wafer contacts to render the wafer a cathode, a plating chamber having a plating bath that contacts both the wafer and the anode, and a source of plating power. Various configurations of these elements may be employed.

[0028] With reference to **FIG. 1**A, there is shown a reactor assembly **20** for electrochemically processing a microelectronic workpiece, such as a semiconductor wafer **25**. The particular reactor shown here is configured to execute an electroplating process on the workpiece **25**.

[0029] Generally stated, the reactor assembly **20** is comprised of a reactor head **30** and a corresponding reactor base, shown generally at **33** and described in detail below, in which the electroplating solution is disposed. This type of reactor assembly is particularly suited for effecting electroplating of semiconductor wafers or like workpieces, in which an electrically conductive, thin-film layer of the wafer is electroplated with a blanket or patterned metallic layer. It will be recognized, however, that the general reactor configuration of **FIG. 1A** is suitable for other workpiece processes as well.

[0030] The reactor head **30** of the electroplating reactor **20** is preferably comprised of a stationary assembly **70** and a rotor assembly **75**. Rotor assembly **75** is configured to receive and carry an associated wafer **25** or like workpiece, position the wafer in a process-side down orientation within reactor container **35**, and to rotate or spin the workpiece while joining its electrically-conductive surface in the plating circuit of the reactor assembly **20**. The rotor assembly **75** includes one or more cathode contacts that provide electroplating power to the surface of the wafer. In the illustrated embodiment, a contact assembly is shown generally at **85** and is described in further detail below. It will be recognized, however, that backside contact may be implemented in lieu of front side contact when the substrate is conductive or other means are used to make electrical contact between the front and back sides of the workpiece.

[0031] The reactor head **30** is typically mounted on a lift/rotate apparatus which is configured to rotate the reactor head **30** from an upwardly-facing disposition in which it receives the wafer to be plated, to a downwardly facing disposition in which the surface of the wafer to be plated is positioned so that it may be brought into contact with the electroplating solution in reactor container **35**, either planar or at a given angle. A robotic arm, which preferably includes an end effector, is typically employed for placing the wafer **25** in position on the rotor assembly **75**, and for removing the plated wafer from within the rotor assembly. The contact assembly **85** may be operated between an open state that allows the wafer to be placed on the rotor assembly **75**, and a closed state that secures the wafer to the rotor assembly and brings the electrically conductive components of the contact assembly **85** into electrical engagement with the surface of the wafer that is to be plated.

[0032] Processing Container

[0033] **FIG. 1B** illustrates the construction of one type of processing container **33**. As illustrated, the processing container **33** generally comprises a main fluid flow chamber **105**, an antechamber **110**, a fluid inlet **115**, a plenum **120**, a flow guide **125** separating the plenum **120** from the antechamber **110**, and a nozzle/slot assembly **130** separating the plenum **120** from the main chamber **105**. These components cooperate to provide a flow (here, of the electroplating solution) at the wafer **25** with a substantially radially independent normal component. In the illustrated embodiment, the impinging flow is centered about central axis **135** and possesses a nearly uniform component normal to the surface of the wafer **25**. This results in a substantially uniform mass flux to the wafer surface that, in turn, enables substantially uniform processing thereof.

[0034] Processing fluid is provided through inlet **115** disposed at the bottom of the container **35**. The fluid from the inlet **115** is directed therefrom at a relatively high velocity through antechamber **110**. In the illustrated embodiment, antechamber **110** includes an accelerated region **140** through which the processing fluid flows radially from the fluid inlet **115** toward fluid flow region **145** of antechamber **110**. Fluid flow region **145** has a generally inverted U-shaped cross-section that is substantially wider at its outlet region proximate flow guide **125** than at its inlet region proximate region **140**. This variation in the cross-section assists in removing any gas bubbles from the processing fluid before the processing fluid is allowed to enter the main chamber **105**. Gas bubbles that would otherwise enter the main chamber **105** are allowed to exit the processing container **35** through a gas outlet disposed at an upper portion of the antechamber **110**.

[0035] Processing fluid within antechamber **110** is ultimately supplied to main chamber **105**. To this end, the processing fluid is first directed to flow from a relatively high-pressure region **150** of the antechamber **110** to the comparatively lower-pressure plenum **120** through flow guide **125**. Nozzle assembly **130** includes a plurality of nozzles or slots **155** that are disposed at a slight angle with respect to horizontal. Processing fluid exits plenum **120** through nozzles **155** with fluid velocity components in the vertical and radial directions.

[0036] Main chamber **105** is defined at its upper region by a contoured sidewall **160** and a slanted sidewall **165**. The contoured sidewall **160** assists in preventing fluid flow separation as the processing fluid exits nozzles **155** (particularly the uppermost nozzle(s)) and turns upward toward the surface of wafer **25**. Beyond breakpoint **170**, fluid flow separation will not substantially affect the uniformity of the normal flow. As such, sidewall **165** can generally have any shape, including a continuation of the shape of contoured sidewall **160**. In the specific embodiment disclosed here, sidewall **165** is slanted and, as will be explained in further detail below, is used to support one or more anodes.

[0037] In those instances in which the processing base **33** forms part of an electroplating reactor, the processing base

33 is provided with one or more anodes or other electrically conductive elements. In the illustrated embodiment, a principal anode **180** is disposed in the lower portion of the main chamber **105**. If the peripheral edges of the surface of the wafer **25** extend radially beyond the extent of contoured sidewall **160**, then the peripheral edges are electrically shielded from principal anode **180** and reduced plating will take place in those regions. However, if plating is desired in the peripheral regions, one or more further anodes may be employed proximate the peripheral regions. Here, a plurality of annular anodes **185** are disposed in a generally concentric manner on slanted sidewall **165** to provide a flow of electroplating current to the peripheral regions. An alternative embodiment would include a single anode or multiple anodes with no shielding from the contoured walls to the edge of the wafer.

[**0038**] The anodes **180**, **185** may be provided with electroplating power in a variety of manners. For example, the same or different levels of electroplating power may be multiplexed to the anodes **180**, **185**. Alternatively, all of the anodes **180**, **185** may be connected to receive the same level of electroplating power from the same power source. Still further, each of the anodes **180**, **185** may be connected to receive different levels of electroplating power to compensate for the variations in the resistance of the plated film. An advantage of the close proximity of the anodes **185** to the wafer **25** is that it provides a high degree of control of the radial film growth resulting from each anode. Preferably, electrical connection to the anodes **180**,**185** are established through connector elements **187**.

[**0039**] Anodes **180**, **185** may be consumable, but are preferably inert and formed from platinized titanium or some other inert conductive material. However, as noted above, inert anodes tend to evolve gases that can impair the uniformity of the plated film. To reduce this problem, as well as to reduce the likelihood of the entry of bubbles into the main processing chamber **105**, processing container **35** includes several unique features. With respect to anode **180**, a small fluid flow path **190** is provided between the underside of anode **180** and antechamber **110**. This results in a Venturi effect that causes the processing fluid proximate the surfaces of anode **180** to be drawn into antechamber **110** and, further, provides a suction flow that affects the uniformity of the impinging flow at the central portion of the surface of the wafer.

[**0040**] As illustrated, the overall reactor assembly **200** is comprised of the processing container **35** along with a corresponding exterior cup **205**. Processing container **35** is disposed within exterior cup **205** to allow exterior cup **205** to receive spent processing fluid that overflows from the processing container **35**. A flange **215** extends about the assembly for securement with, for example, the frame of the corresponding tool.

[**0041**] FIGS. 2A-2G illustrate one method of filling a trench and via formed on the surface of a semiconductor wafer wherein the electrochemically deposited copper layer may be applied using the apparatus described in connection with **FIG. 1**. **FIG. 2A** illustrates a second assembly **400** having an area **405** that is to be connected by copper metallization. In **FIG. 2B** a layer **410** of dielectric material, such as silicon dioxide or a low-K dielectric material, is deposited over the second assembly **400** including over area **405**. Through a photoresist process and reactive ion etch or the like, selective portions of layer **410** are removed to form, for example, a trench **415** and via **420** into which copper metallization is to be deposited. The end structure is shown in the perspective view of **FIG. 2C** wherein the via **420** overlies connection area **405** and trench **415** overlies via **420**. Connection area **405** may be, for example, a metallization feature above the substrate.

[**0042**] As shown in **FIG. 2D, a** barrier layer **423** and seed layer **425** may be disposed on the surface of dielectric layer **410**. The barrier layer may be, for example, tantalum or titanium nitride. The barrier layer **423** is typically used when the structure **405** is susceptible to contamination from copper or the seed layer metal, and/or when the seed layer metal or copper may readily migrate through the dielectric layer **410** and contaminate other portions of the microelectronic circuit. As such, barrier layer **423** should be sufficiently thick along the contour of the trenches and vias to act as a diffusion barrier. Layer **423** may also function as an adhesion layer to facilitate binding between the seed layer **425** and the dielectric **410**. If, however, the structure **405** is not susceptible to such contamination, there is sufficient adhesion, and the dielectric layer **410** itself acts as a barrier layer, then a separate barrier layer **423** may not be necessary. The seed layer **425** may, for example, be a copper layer or other conductive metal layer and is preferably at least 200 Angstroms thick at its thinnest point. Sidewalls **430** of the trench **415** and via **420** as well as the bottom of via **420** should be covered by the seed layer **425** and barrier layer **423** to facilitate a subsequent electrochemical copper deposition step. The seed layer **425** may be deposited through, for example, a CVD or PVD process.

[**0043**] The semiconductor wafer with the seed layer **425** is subject to a subsequent electrochemical copper deposition process. The electrochemical copper deposition process is executed so as to form numerous nucleation sites for the copper deposition to thereby form grain sizes that are substantially smaller than the characteristic dimensions of the via **420** and trench **415**. An exemplary structure having such characteristics is illustrated in **FIG. 2E** wherein layer **440** is a layer of copper metallization that has been deposited using an electrochemical deposition process.

[**0044**] As shown in **FIG.** 2E, the copper metallization **440** formed in the electrochemical deposition process is deposited over the seed layer **425** and extends a distance above the surface of dielectric layer **410**. Since the only features that are to contain the metallization are the via **420** and trench **415**, excess copper above the dielectric layer **410** must be removed. Removal of the excess copper above the upper surface of the dielectric layer **410** may be executed using a chemical mechanical polish technique. An exemplary structure in which such removal has taken place is illustrated in **FIG. 2F**. After such removal, a capping barrier layer **445** may be disposed, for example, over the entire surface of the wafer, or the processes set forth in FIGS. 2A-2F may be repeated without a capping barrier layer **445** whereby the trench **415**, now filled with copper metallization, corresponds to the structure **405** that further copper metallization is to contact.

[**0045**] The process illustrated in FIGS. 2A-2G indicates that the via **420** and trench **415** are formed together. However, it will be recognized that the structures may be generally formed and filled separately in accordance with the single-damascene process described above. In such instances, the via **420** is first plated in accordance with the steps set forth in FIGS. **2A-2F** while the trench **415** is subsequently plated in accordance with the steps set forth in FIGS. **2A-2F** after plating of the via **420** has been completed. In effect, the via **420** corresponds to the structure **405** during plating of the trench **415**. The thermal reactor and associated methods disclosed herein are suitable for use in both single-damascene and multi-damascene processes.

[0046] A comparison between **FIGS. 2E and 2F** reveals that an increase in the grain size of the copper layer **440** has taken place. This change in the grain size is purposely accelerated in accordance with the present invention by subjecting the microelectronic workpiece to an annealing process in the thermal reactor disclosed below. In such an annealing process, the wafer is raised to an elevated temperature that is above the ambient temperature conditions normally found in a clean room. The annealing preferably takes place at a temperature at or below about 250-300 degrees Celsius, or at least below the temperature at which the material used for the dielectric layer begins to degrade. Annealing at these temperatures is particularly advantageous when the dielectric layer is formed from a low-K dielectric material since such materials may begin to degrade at elevated temperatures above 300 degrees Celsius.

[0047] Annealing is particularly advantageous when used prior to chemical mechanical polishing (CMP). CMP involves the use of mechanical and chemical forces to remove copper that is deposited in excess of what is desired for interconnects (see **FIGS. 2E and 2F**). In accordance with the present invention, the accelerated annealing process stabilizes the grain structure of the copper film by significantly reducing the amount of time required for film recrystallization to occur (i.e. transforming many small grains into fewer large grains). The accelerated annealing process, in accordance with the present invention, also minimizes the variation in the grain size distribution which is seen to occur during a room-temperature self-annealing process. The CMP polish rate, or removal rate, is seen to vary as a direct result of the grain size of the copper film. The initial, small grained (i.e. many grain boundaries) films are seen to polish slower (at least with a particular CMP slurry) than large grained films. Similarly, the uniformity of the CMP polish is seen to vary as a direct result of the grain size uniformity of the copper film. Therefore, in accordance with the present invention, the accelerated annealing process reduces the time required for the CMP process, while improving its uniformity, predictability and repeatability.

[0048] **FIGS. 3A and 3B** illustrate a thermal reactor, shown generally at **500**, that is constructed in accordance with one embodiment of the present invention. Generally stated, the thermal reactor **500** includes a first assembly **505**, a second assembly **510**, and one or more actuators **515** that are connected to provide relative movement between the first assembly **505** and second assembly **510**. The configuration of the thermal reactor **500** shown here may be constructed to occupy a minimal amount of space, thereby making it particularly suitable for incorporation as one of a plurality of processing stations in an integrated microelectronic workpiece processing tool.

[0049] In the illustrated embodiment, second assembly **510** includes one or more components **525** that are adapted to receive a single wafer W from an automated wafer transfer mechanism, such as a robot having an end effector that can grasp and release the wafer W. To this end, second assembly **510** may comprise a second assembly housing **550** having an upper rim from which one or more wafer support members **525** extend. Wafer support members **525** may take on a number of different forms. For example, a single wafer support member **525** may be formed as a continuous ring having a lip or the like upon which the wafer W is set by the wafer transfer mechanism. Alternatively, a plurality of wafer support members **525** may be in the form of discrete fingers disposed at various angular positions corresponding to the peripheral edge of the wafer W, the angular positions being chosen to ensure access by the wafer transfer mechanism. Other configurations for the wafer support may likewise be suitable.

[0050] Second assembly **510** of the illustrated embodiment has an interior region in which a thermal transfer unit **560** is disposed. Thermal transfer unit **560**, in turn, comprises a heater **565** and a cooling chuck **570**, the operation of which will be set forth in further detail below. Heater **565** preferably has a relatively low thermal mass so that its temperature response time is fast enough for thermally processing the workpiece within a reasonably defined time period. In contrast, cooling chuck **570** preferably has a high thermal mass when compared to the heater **565** so that the cooling chuck **570** may cool the heater **565** (as will be set forth below) within a reasonably defined time period.

[0051] As noted, actuator **515** provides relative movement between the first assembly **505** and the second assembly **510**. In the illustrated configuration, actuator **515** is connected to move the first assembly **505** to and from engagement with the second assembly **510**. More particularly, actuator **515** includes a lower portion **530** that is in fixed positional alignment with the second assembly **510** since both are secured to a common deck **535**. A transversely extending arm **540** extends from an upper portion **545** of the actuator **515** and engages the first assembly **505**. Actuator **515** is configured to drive the transversely extending arm **540** and the first assembly **505** between a first position in which the wafer W can be loaded onto the second assembly **510** by an automated wafer transfer mechanism, and a second position in which the first assembly **505** and second assembly **510** are disposed proximate one another to form a space or chamber in which the wafer W is processed.

[0052] In operation, actuator **515** initially drives the first assembly **505** to the first position, as illustrated in **FIG. 3A**. While in this position, the wafer W is placed onto the wafer support members **525** of the second assembly **510** by an automated wafer transfer mechanism, such as an articulated robot having an end effector carrying the wafer W.

[0053] Once the wafer W has been loaded onto wafer supports **525**, actuator **515** drives first assembly **505** toward second assembly **510** to the second position illustrated in **FIG. 3B**. The wafer support members **525** translate congruently with the first assembly **505**, through contact with the lower surface of the first assembly **505** or through independent actuation. As illustrated in **FIG. 3**B, the wafer W is deposited directly onto the surface of thermal transfer unit **560**, where it will be thermally processed. Generally, the upper surface of wafer W will be the device side of the workpiece while the non-device, lower surface of wafer W will be placed in contact with the upper surface of thermal transfer unit **560**. To secure wafer W to the upper surface of thermal transfer unit **560** during processing, thermal transfer unit **560** may include one or more apertures (described in detail below) that are connected to a vacuum that suctions the lower surface of wafer W against the upper surface of thermal transfer unit **560**.

[**0054**] In the position of **FIG.** 3B, the lower portion of housing **520** may engage the upper portion of second assembly housing **550** to form a thermal processing chamber **555**, which may or may not be substantially gas-tight. When the thermal reactor **500** is used, as here, for annealing the workpiece, the thermal processing chamber **555** is continuously purged with an inert gas to minimize the level of any oxidizing agents that may form an undesirable oxide with the copper. To facilitate this purge, first assembly **505** may be provided with one or more gas inlet ports **580** and one or more gas outlet ports **585**. Gas inlet port **580** may open to a manifold in housing **520** that, in turn, opens to a plurality of holes disposed through a lower surface of housing **520**. Gas mixtures that are particularly suitable for reducing oxidizing agents in the processing chamber **555** include nitrogen or hydrogen forming gases (5% hydrogen/95% argon). The inert process environment inhibits surface film oxidation of the wafer at elevated temperatures, which can be enhanced by the oxygen-gettering effects of hydrogen forming gas. In processes other than annealing, ports **580** and **585** may be used to provide an inlet and outlet for other gases used to process wafer W.

[**0055**] Other enhancements may be incorporated into the thermal reactor **500** to make it particularly well-suited for single workpiece annealing. For example, the volume of the processing chamber **555** formed by the cooperation of the first assembly **505** and second assembly **510** may be minimized, which makes it more efficient to purge and, thereby, minimizes the consumption of high-purity, inert process gas. In addition, first assembly **505** may be provided with one or more cooling fluid inlet ports **612** and one or more cooling fluid outlet ports **617** that provide a flow of cooling fluid to a lower surface of the housing **520** proximate wafer W that, in turn, assists in cooling the wafer W. Still further, the first assembly housing **520** may contain internal flow channels for re-circulating fluid, to maintain the lower surface of the housing **520** at a specified temperature.

[**0056**] It will be recognized that various fluid inlet and outlet ports may also be affixed to the second assembly **510**. For example, fluid ports may be affixed to the second assembly for use in connection with the cooling chuck **570**. More particularly, a flow of cooling fluid may be provided directly to the cooling chuck or to other structures of the second assembly for cooling of the cooling chuck **570**. Furthermore, one or more exhaust ports may be disposed in the second assembly for supply and/or venting of process gases. This arrangement in which the ports are affixed to the second assembly has the benefit of minimizing the amount of movement imparted to the ports and corresponding connectors, thereby increasing in the overall reliability of the corresponding connections.

[**0057**] **FIGS. 3C and 3D** illustrate a further embodiment of a thermal reactor constructed in accordance with the present invention. In many respects, this embodiment is somewhat similar to the embodiment set forth above in connection with **FIGS. 3A and 3B**. They differ, however, in that the wafer supporting components are disposed on the first assembly **505** as opposed to the second assembly **510**. As such, an automated robot servicing the thermal reactor embodiment of these figures is controlled to place and remove the workpiece to and from the first assembly **505** when the first and second assemblies are in the relative wafer loading position.

[**0058**] In each of the foregoing reactor embodiments, once the wafer W is secured to the thermal transfer unit **560** and the processing chamber **555** has been purged, the heater **565** of thermal transfer unit **560** is directed to ramp up to the target process temperature. Preferably, heating power is provided to heater **565** in the form of electrical energy by a controller using one or more temperature feedback signals for closed-loop control. The wafer W is then held at the processing temperature for a specified length of time. After the expiration of the specified length of time, power is shut off to the heater **565** and the cooling chuck **570** is engaged. In accordance with one manner in which the cooling process takes place, the cooling chuck **570** remains engaged until the temperature drops below a predetermined temperature threshold, such as 70 degrees Celsius, after which the cooling chuck **570** may be disengaged. As such, the wafer W is cooled to a temperature that allows it to be safely handled by the wafer transfer mechanism as well as in subsequent processing chambers. Further, the wafer W is cooled to a temperature at which the electroplated metal is less susceptible to oxidizing agents in the ambient atmosphere before it is removed from the inert atmosphere of the processing chamber **555**.

[**0059**] Upon completion of the cool-down cycle, the vacuum circuit that is used to secure wafer W against thermal transfer unit **560** is deactivated and the actuator **515** drives first assembly **505** back to the position illustrated in **FIG. 3A** or **FIG.** 3C, depending on the particular embodiment. As the first assembly **505** is raised in the embodiment of **FIGS. 3A and 3B**, wafer support members **525** naturally engage or are otherwise directed to engage and lift wafer W from the surface of the thermal transfer unit **560**. The automated wafer transfer mechanism then removes wafer W from wafer support members **525**, thereby leaving the thermal reactor **500** ready for accepting and processing another wafer W. While thermal reactor **500** is waiting to accept another wafer W, heater **565** may be directed to begin ramping to the desired processing temperature, or some intermediate temperature, to thereby reduce the overall time required to thermally process the next microelectronic workpiece. Similarly, wafer support members **525** of the embodiment shown in **FIG. 3C** are directed to release the wafer W to the automated wafer transfer mechanism thereby leaving the reactor **500** in a state in which it is ready to receive a further wafer.

[**0060**] FIGS. 4A-4F illustrate different embodiments of the heater **565**, employing different substrate configurations. Preferably, heater **565** is constructed as a thick film heater (i.e., a heater that is constructed using thick film patterning techniques) having a low thermal mass. Each thick film heater **565** configuration can accommodate a high power density within a thin physical profile, resulting in a low thermal mass with fast thermal response (i.e. faster heating and cooling). Given the low thermal mass of such thick film heater configurations, the thick film heater **565** should be thermally isolated from other structures in the second assembly **510**.

[0061] FIG. 4A illustrates a basic thick film heater. As shown, the thick film heater **565** is comprised of a high resistance layer **600** that is disposed between two ceramic substrate layers **605**.

[0062] FIG. 4B illustrates a further construction of the thick film heater **565**. As shown, thick film heater **565** may be fabricated by forming a layer **600** having a circuit pattern of high resistance traces **604** between two or more thin ceramic substrates **605**, with optional vacuum distribution circuit channels **603** embedded between the high electrical resistance traces **604**. When employed, the vacuum distribution circuit channels **603** are connected to an exterior vacuum supply **607**. The high resistance traces **604** may be formed in a pattern that tailors the power distribution to the shape of the microelectronic workpiece so that the workpiece is uniformly heated. The optional vacuum circuit channels **603** are connected to apertures **606** in the top substrate layer, thereby providing suction to the lower surface of the microelectronic workpiece. The embodiments illustrated in **FIGS. 4A and 4B** are particularly suited for those instances in which a ceramic interface is desired between the heater **565** and the cold chuck **570**.

[0063] FIG. 4C illustrates a third manner in which the thick film heater **565** may be constructed. As shown, the thick film heater **565** may be fabricated with two or more layers of thin ceramic substrate **605** that sandwich a layer of vacuum circuit channels, with a layer of high electrical resistance traces **600** deposited onto the bottom surface of the thick film heater **565**. A layer of dielectric overglaze **601** is deposited over the high electrical resistance traces **604** for protection and electrical isolation. This embodiment is relatively easy to manufacture since the vacuum distribution channels **603** may be cut completely through the second ceramic layer **605** and have the rear side thereof sealed by a lower, adjacent ceramic layer.

[0064] FIG. 4D illustrates a fourth manner in which the thick film heater **565** may be constructed. As shown, thick film heater **565** may be fabricated with three or more laminated layers of thin ceramic substrate **605** that sandwich a layer of vacuum circuit channels between two or more thin ceramic substrates **605**, and a lower layer of high electrical resistance traces **600** between a different pair of ceramic substrates **605**. Again, this embodiment is relatively easy to manufacture since the vacuum distribution channels **603** are cut completely through the second ceramic layer and are sealed by a lower, adjacent ceramic layer. Further, this embodiment is particularly well-suited for those instances in which it is desired to have a ceramic interface between the heating chuck **565** and the cold chuck **570**.

[0065] FIG. 4E illustrates a fifth manner in which the thick film heater **565** may be constructed. As shown, thick film heater **565** may be fabricated with one layer of thin ceramic substrate **605**, with a layer of high electrical resistance traces **600** deposited onto the bottom surface of the thick film heater **565**. A layer of dielectric overglaze **601** is deposited over the high electrical resistance traces **604** for protection and electrical isolation. The void between the bottom surface of the thick film heater **565** and the top surface of the cooling chuck **570** serves as a vacuum reservoir for the apertures **606** that extend through the thick film heater **565**.

[0066] FIG. 4F illustrates an embodiment of heater **565** that may be used to provide good thermal contact between the upper surface of heater **565** and the wafer W during a heating cycle and the lower surface of the heater **565** and the cooling chuck **570** during a cooling cycle. To this end, the second of the ceramic layers **605** is provided with at least one set of vacuum distribution channels **603***a*. The vacuum distribution channels **603** are in fluid communication with one or more apertures **606** disposed through the upper ceramic substrate that is used to contact the wafer W. The vacuum distribution channels **603** are also in fluid communication with one or more apertures **609** disposed through a lower surface of the heater **565**. Vacuum equipment **607** operates during both the heating and the cooling cycles. During the cooling cycle, the vacuum provided through apertures **609** assists in establishing thermal contact between the lower surface of the heater **565** and the cooling chuck **570**.

[0067] Alternatively, separate vacuum distribution channels **603** may be connected to separately operable vacuum sources **607** and **608**. In such instances, the first vacuum source and corresponding vacuum distribution channels may be used to bring the wafer W into firm thermal contact with the upper surface of the heater **565** while the second vacuum source and corresponding vacuum distribution channels may be used to bring the cooling chuck **570** into firm thermal contact with the lower surface of the heater **565** during a cooling cycle.

[0068] FIGS. 4G-4J are exemplary plan views of various elements used in the thick film heaters shown in FIGS. 4B-4F. FIG. 4G is a plan view of an exemplary layout for the high resistance layer **600**. As illustrated, the exemplary layout comprises a plurality of concentric high resistance traces **604** that are separated from one another by corresponding concentric isolation regions. Isolation regions **611** may be comprised of a dielectric material, such as ceramic or air. When air is used as the dielectric material, isolation regions **611** may be used as the vacuum distribution channels **603** of an embodiment such as the one illustrated in **FIG. 4B**. Each of the high resistance traces **604** includes electrical nodes that are isolated from one another by corresponding isolation regions **613**. Isolation regions **613** may be comprised of a dielectric material, such as ceramic or air. Additionally, the conductors **604** may be provided with power on an individual basis, or may be provided with power supplied on a common power bus **619**.

[0069] FIG. 4H is an exemplary plan view of the layout of vacuum distribution channels **603** formed in the second ceramic layer **605** of an embodiment such as the one illustrated in **FIGS. 4C, 4D** and 4F. Again, the vacuum distribution channels **603** are formed in a concentric arrangement that are generally isolated from one another by corresponding isolation regions **614**. Isolation regions **614** include one or more fluid passage channels **617** that provide areas of fluid communication between the distribution channels **603** so that the vacuum provided by a vacuum source connected to one or more of the distribution channels **603** may be communicated to all of the distribution channels.

[0070] FIG. 4I is a top plan view of an exemplary layout for the uppermost ceramic layer **605**. As illustrated, apertures **606** may be formed in the upper ceramic layer **605** at locations disposed immediately above the vacuum flow channels **603** (shown in phantom outline). With respect to the exemplary layout shown here, the apertures **606** are arranged in concentric circles at equal angular intervals.

[**0071**] **FIG. 4J** illustrates a further configuration for the high resistance traces **604**. As shown, the traces **604** are organized in the form of a continuous spiral separated by a isolation regions **611** that, as noted above, can be formed from a solid dielectric material or air. When air is employed, regions **611**, in certain of the foregoing embodiments, can function as the vacuum flow channels **603**.

[**0072**] FIGS. **5**-**8** illustrate various embodiments of the thermal transfer unit **560** employing different interfaces between the thick film heater **565** and cooling chuck **570**. In the embodiment shown in **FIGS. 5A and 5B**, solid/solid conduction is used as the primary mode of heat transfer from the thick film heater **565** to the cooling chuck **570** as well as for the heat transfer between the heater **565** and wafer W. During thermal processing of the wafer W, the thermal transfer unit **560** is in the heating state illustrated in **FIG. 5A**. In the heating state, the top surface of cooling chuck **570** is offset from the lower surface of the thick film heater **565** and the volume between them is filled with a relatively low thermal conductivity gas, such as nitrogen, which thermally insulates the elements from one another. Isolating the thick film heater **565** from the cooling chuck **570** in this manner facilitates a fast heat up to the desired process temperature, because there is minimal heat loss. The cool-down state is illustrated in **FIG. 5B**. In this state, the thick film heater **565** is deactivated and the thick film heater **565** and cooling chuck **570** are moved relative to one another so that the lower surface of thick film heater **565** engages the upper surface of cooling chuck **570**. Such relative movement may be provided, for example, by opposing inflatable, flange seals that are actuated to impart vertical movement to the cooling chuck **570**.

[**0073**] **FIGS. 6A and 6B** illustrate an embodiment of the thermal transfer unit **560** in which solid/gas/solid conduction is used as the primary mode of heat transfer from the thick film heater **565** to the cooling chuck **570**. In this embodiment, the thick film heater **565** and cooling chuck **570** are permanently offset from one another by a very small distance (i.e., 0.020 inches). While in the heating state illustrated in **FIG. 6**A, the volume **569** between the thick film heater **565** and the cooling chuck **570** is purged with a relatively low thermal conductivity gas to thermally insulate the elements from one another. When in the cooling state illustrated in **FIG. 6**B, the thick film heater **565** is deactivated and the volume **569** between the thick film heater **565** and the cooling chuck **570** is purged with a relatively high thermal conductivity gas, such as helium, which serves as the medium for conducting heat from the thick film heater **565** to the cooling chuck **570**. This approach provides efficient use and transfer of thermal energy, with no moving parts. Notably, inlet and outlet ports for the gases must be provided in thermal reactor **500**.

[**0074**] **FIGS. 7A and 7B** illustrate an embodiment of thermal transfer unit **560** that makes use of forced convection and boiling as the primary modes to transfer heat from the thick film heater **565** to the cooling chuck **570**. Again, the thick film heater **565** and cooling chuck **570** are permanently offset from one another by a small distance (i.e., 0.020-0.040 inches). While in the heating state illustrated in **FIG. 7**A, the volume **569** between the thick film heater **565** and cooling chuck **570** is purged with a relatively low thermal conductivity gas to thermally insulate the elements from one another. When in the cooling state illustrated in **FIG. 7**B, the thick film heater **565** is deactivated and the volume **569** between the heating chuck **565** and the cooling chuck **570** is filled with an impinging, high-speed flow of heat transfer fluid (i.e., water or glycol), which serves as the medium for convecting heat away from the thick film heater **565** to the cooling chuck **570**. The cooling chuck **570** in this instance may be formed to serve as a sparger shower assembly, uniformly delivering the heat transfer fluid through a manifold of flow jet apertures **572** in the upper surface of the cooling chuck, and locally draining the fluid through an interspersed manifold of exit holes **573**. Alternatively, spent cooling fluid may be directed to exit radially in the channel between the heating and cooling chucks. This overall approach provides efficient use and transfer of thermal energy, again with no moving parts.

[**0075**] **FIGS. 8A and 8B** illustrate yet a further embodiment of the thermal transfer unit **560**. In this embodiment, the wafer W, thick film heater **565** and cooling chuck **570** are in constant contact during the entire thermal processing cycle. A thin layer of insulating material **633** is used to thermally insulate the thick film heater **565** from the cooling chuck **570**. The material used for layer **633** and the thickness thereof are chosen to yield an optimal balance between the performance of the thermal transfer unit **560** that is exhibited during the heating and cooling sub-cycles of the overall thermal processing cycle. This design offers the advantage of design simplicity, in that there are no moving parts and no thermally insulating/conducting gases needed.

[**0076**] In each of the foregoing embodiments in which the cooling chuck **570** directly contacts the heater **565**, an optional, high thermal conductivity material may be disposed between the contact surfaces during the cooling cycle. The material disposed between the contact surfaces preferably is resiliently deformable in response to the pressure applied when the heater **565** and cooling chuck **570** are in direct thermal contact with one another. In this way, a more uniform thermal transfer medium exists between the heater **565** and cooling chuck **570** since air pockets or the like that may otherwise occur if the heater **565** and cooling chuck **570** surfaces were in direct physical contact are substantially eliminated.

[**0077**] Due to its ready implementation in a compact architecture, thermal reactor **500** may be integrated with a wet-chemical processing tool that is capable of electrochemical deposition of a metal, such as copper. One such processing tool is the LT-210™ electroplating apparatus available from Semitool, Inc., of Kalispell, Mont. **FIGS. 9 and 10** illustrate such integration.

[**0078**] The system of **FIG. 9** includes a plurality of processing stations **610**. Preferably, these processing stations include one or more rinsing/drying stations and one or more electroplating stations (including one or more electroplating reactors such as the one illustrated in **FIGS. 1A and 1B**), although further wet-chemical processing stations may also be employed. The system also preferably includes an annealing station, such as at **615**, that includes at least one thermal reactor, constructed in accordance with one or more of the foregoing embodiments, for executing an annealing process on each workpiece. The workpieces are transferred between the processing stations **610** and the annealing station **615** using one or more robotic transfer mechanisms **620** that are disposed for linear movement along a central track **625**.

[0079] **FIG. 10** illustrates a further manner in which an annealing station **635**, located in portion **630**, that includes at least one thermal reactor, may be integrated in a wet-chemical processing tool set. Unlike the embodiment of **FIG. 9**, in this embodiment, at least one thermal reactor is serviced by a dedicated robotic mechanism **640**. The dedicated robotic mechanism **640** accepts workpieces that are transferred to it by the robotic transfer mechanisms **620**. Transfer may take place through an intermediate staging door/area **645**. As such, it becomes possible to hygienically separate the annealing portion **630** of the processing tool from other portions of the tool. Additionally, the illustrated annealing station may be implemented as a separate module that is attached to upgrade an existing tool set.

[0080] **FIG. 11** illustrates one manner in which two or more thermal reactors constructed in accordance with one or more of the foregoing embodiments may be consolidated at a single annealing station, such as at station **615** of **FIG. 9** and station **635** of **FIG. 10**. In this embodiment, the thermal reactors are disposed in a stacked configuration within a housing unit **700**. Housing unit **700** includes a plurality of chamber units **710**, each including a single thermal reactor. The chamber units **710** are defined by upper and lower horizontal walls **715** and **720**, and one or more sidewalls **725**. One or more sidewalls **725** of each chamber unit **710** may include an automated door or mail slot opening **730** that isolates each chamber unit **710** from the surrounding environment and provides the wafer transfer mechanism with access to the thermal reactors during wafer loading and unloading operations. Processed wafers may be transferred directly to a chemical mechanical polishing tool from either of the processing tools of **FIGS. 9 and 10**.

[0081] **FIG. 12** is a schematic block diagram of one embodiment of a programmable control system that may be used to control the thermal reactor assembly in accordance with a further aspect of the present invention. The control system, shown generally at **900**, comprises a programmable controller **905**, such as a programmable logic controller, microcontroller, microprocessor, etc. Controller **905** receives data and communicates data to and from a plurality of peripheral components that are used to monitor and control the thermal reactor. For example, controller **905** is in communication with an automated gas flow meters/valve system **910**. The automated gas flow meters/valve system **910** controls the flow of various gases, such as the purging gases, that are provided to the thermal reactor. The automated gas flow system **910** may also be used to control the operation of the vacuum equipment **607** and/or **608** shown in FIGS. **4**B-**4**F, turning the equipment on and off at the appropriate times.

[0082] Control of the annealing temperature within the thermal reactor may also be controlled by the controller **905** through a corresponding interface with a chuck temperature sensor/supply system **915**. The chuck temperature sensor/supply system **915** includes a plurality of temperature sensors that are used to monitor the temperature within the thermal reactor. The system **915** also comprises a power supply that provides the necessary electrical power to the electrical traces **604** (FIGS. **4**A-**4**F) of the high resistance layer in response to data communicated from the controller **905**. Various known temperature control algorithms may be employed within the programmable controller **905** to facilitate this function.

[0083] Element drive system **920** and chuck cooling assembly **925** are used to operate the drive **530** (FIGS. **3**A-**3**D) and the cooling chuck **570**, respectively. More particularly, drive system **920** operates the drive **530** to move the first and second assemblies **510, 520** with respect to one another for loading/unloading and processing of the wafer W in response to commands received from programmable controller **905**. The drive system **920** may also communicate positional information to the controller **905** indicative of the relative position of the first and second assemblies **510, 520**, which may be used by the controller **905** to properly position the assemblies during operation of the thermal reactor.

[0084] Chuck cooling assembly system **925** may serve a dual purpose. First, the system **925** may be used to control the relative movement between the heating chuck **565** and cooling chuck **570** in response to commands received from the controller **905**. Further, system **925** may be used to control the temperature of the cooling chuck **570** by controlling the cooling gases provided to the cooling chuck in response to commands received from the controller **905**. To this end, system **925** may also include one or more temperature sensors that monitor the temperature of the cooling chuck **570** and transmit data to the controller **905** indicative of this temperature. The controller **905** may then use this temperature information to direct system **925** to cool the cooling chuck **570** to the target temperature.

[0085] Controller **905** also communicates with one or more safety shutdown elements **930**. The safety shutdown elements **930** are activated by the controller **905** when the controller detects one or more conditions that compromise the safety of the thermal reactor. For example, the safety shutdown elements **930** may be used by the controller **905** to shutdown the thermal reactor system in response to an over temperature condition of the heating chuck, reactor chamber, etc. It will be recognized in view of these teachings that other safety conditions may also be detected by the controller **905** pursuant to activation of the safety shutdown elements **930**.

[0086] Numerous modifications may be made to the foregoing system without departing from the basic teachings thereof. Although the present invention has been described in substantial detail with reference to one or more specific embodiments, those of skill in the art will recognize that changes may be made thereto without departing from the scope and spirit of the invention.

1. An apparatus for thermally processing a microelectronic workpiece, the apparatus comprising:

a first assembly;

a second assembly disposed opposite the first assembly,

one or more elements arranged to support the microelectronic workpiece on the either the first or second assemblies, the one or more elements further being arranged to facilitate automatic loading and unloading of the microelectronic workpiece;

an actuator disposed to provide relative movement between the first assembly and second assembly between at least a loading position in which the first assembly and the second assembly are in a state for loading or unloading of the microelectronic workpiece, and a thermal processing position in which the first assembly and second assembly are proximate one another and form a thermal processing chamber;

a thermal transfer unit disposed in the second assembly, the thermal transfer unit having a workpiece support surface that is heated and cooled in a controlled manner, the one or more elements of the second assembly bringing a surface of the microelectronic workpiece into direct physical contact with the workpiece support surface of the thermal transfer unit as the first assembly and second assembly are driven to the thermal processing position by the actuator.

2. An apparatus as claimed in claim 1 wherein the thermal transfer unit comprises:

a thick film heater assembly having a first surface forming the wafer support surface of the thick film heater, and a second surface opposite the first surface; and

a cooling chuck having a surface proximate the second surface of the thick film heater.

3. An apparatus as claimed in claim 1 wherein the thermal transfer unit comprises:

a low thermal mass heater; and

a high thermal mass cooler disposed to controllably cool the low thermal mass heater.

4. An apparatus as claimed in claim 2 wherein the thick film heater comprises

a ceramic layer substrate having a first side thereof forming the wafer support surface;

a circuit pattern of high electrical resistance traces in high thermal communication with the ceramic layer substrate; and

a layer of dielectric overglaze disposed between and over the high electrical resistance traces and forming the second surface of the heating chuck; and

a plurality of vacuum apertures disposed through all layers of the thick film heater

5. An apparatus as claimed in claim 2 and further comprising a layer of material disposed between and concurrently in physical contact with both the thick film heater and the cooling chuck.

6. An apparatus as claimed in claim 5 wherein the layer of material comprises a ceramic fabric.

7. An apparatus as claimed in claim 2 wherein the surface of the cooling chuck physically contacts the second surface of the thick film heater when cooling the thick film heater.

8. An apparatus as claimed in claim 4 wherein the cooling chuck is movable with respect to the thick film heater between a first position in which the surface of the cooling chuck is physically disengaged from the second surface of the thick film heater and a second position in which the surface of the cooling chuck directly contacts the second surface of the thick film heater.

9. An apparatus as claimed in claim 2 wherein a flow of a low thermal conductivity gas is provided between the surface of the cooling chuck and the second surface of the thick film heater while in the first position.

10. An apparatus as claimed in claim 2 wherein the cooling chuck is movable with respect to the thick film heater between a first position in which the surface of the cooling chuck is physically disengaged from the second surface of the thick film heater and a second position in which the surface of the cooling chuck directly contacts the second surface of the thick film heater, and wherein a vacuum circuit facilitates suction contact force between the surface of the cooling chuck and the second surface of the thick film heater while in the second position.

11. An apparatus as claimed in claim 8 wherein the cooling chuck is movable with respect to the thick film heater between a first position in which the surface of the cooling chuck is physically disengaged from the second surface of the thick film heater and a second position in which a surface of the cooling chuck directly contacts the second surface of the thick film heater, and wherein a vacuum circuit facilitates suction contact force between the surface of the cooling chuck and the second surface of the thick film heater while in the second position.

12. An apparatus as claimed in claim 2 wherein the surface of the cooling chuck and the second surface of the thick film heater are separated from one another by a flow channel during heating and cooling sub-cycles of an overall thermal processing cycle.

13. An apparatus as claimed in claim 12 wherein a low thermal conductivity fluid and/or gas is provided in the flow channel during the heating sub-cycle and a high thermal conductivity fluid and/or gas is provided in the flow channel during the cooling sub-cycle.

14. An apparatus as claimed in claim 13 wherein the low thermal conductivity fluid and/or gas comprises nitrogen or argon, or a mixture thereof.

15. An apparatus as claimed in claim 13 wherein the high thermal conductivity fluid and/or gas comprises helium.

16. An apparatus as claimed in claim 12 wherein the surface of the cooling chuck is provided with a plurality of apertures through which an impinging, high-speed flow of a heat transfer fluid is provided during a cooling sub-cycle into the flow channel for contact with the second surface of the thick film heater.

17. An apparatus as claimed in claim 16 wherein the heat transfer fluid comprises a fluid selected from the group consisting of water and glycol.

18. An apparatus as claimed in claim 2 wherein the thick film heater comprises:

one or more ceramic substrate layers; and

a circuit pattern of high electrical resistance traces, arranged according to the shape of the microelectronic workpiece and to optimize the temperature uniformity of the microelectronic workpiece during the thermal processing cycle; and

vacuum channels for suction of the microelectronic workpiece contact surface onto the microelectronic workpiece support surface of the thermal transfer unit.

19. An apparatus as claimed in claim 2 wherein the thick film heater comprises

a ceramic layer substrate;

a circuit pattern of high electrical resistance traces in high thermal communication with the ceramic layer substrate; and

a layer of dielectric overglaze disposed between and over the high electrical resistance traces; and

a plurality of vacuum apertures disposed through all layers of the thick film heater

20. An apparatus as claimed in claim 2 wherein the thick film heater comprises:

first and second ceramic layers;

a circuit pattern of high electrical resistance traces are disposed between and in high thermal communication with the first and second ceramic layers; and

one or more vacuum circuit channels disposed between the high electrical resistance traces, and connected to a plurality of apertures in the first ceramic layer.

21. An apparatus as claimed in claim 2 wherein the thick film heater comprises:

first and second ceramic layers; and

a circuit pattern of high electrical resistance traces disposed between and in high thermal communication with the first and second ceramic layers; and

a plurality of vacuum apertures disposed through all layers of the thick film heater.

22. An apparatus as claimed in claim 2 wherein the thick film heater comprises:

first and second ceramic layers; and

a circuit pattern of high electrical resistance traces disposed in thermal communication with the first and second ceramic layers; and

a layer of dielectric overglaze disposed between and over the high electrical resistance traces; and

one or more vacuum circuit channels disposed between the first and second ceramic layers, and connected to a plurality of apertures in the first ceramic layer.

23. An apparatus as claimed in claim 2 wherein the thick film heater comprises:

first, second and third ceramic layers, the second ceramic layer being disposed between the first and third ceramic layers; and

a circuit pattern of high electrical resistance traces disposed in high thermal communication with the first, second and third ceramic layers; and

a layer of dielectric overglaze disposed between and over the high electrical resistance traces; and

one or more vacuum circuit channels disposed in the second ceramic layer, and connected to a plurality of apertures in the first ceramic substrate layer.

24. An apparatus for applying a metal to the surface of a microelectronic workpiece, the apparatus comprising:

one or more processing stations adapted to deposit the metal on the surface of the microelectronic workpiece using an electrochemical deposition process; and

one or more annealing stations having at least one thermal reactor, the at least one thermal reactor comprising

a first assembly;

a second assembly disposed opposite the first assembly,

one or more elements arranged on either the first or second assembly to support the microelectronic workpiece, the one or more elements further being arranged to facilitate automatic loading and unloading of the microelectronic workpiece;

an actuator disposed to provide relative movement between the first assembly and second assembly between at least a loading position in which the first assembly is in a state for loading or unloading of the microelectronic workpiece, and a thermal processing position in which the first assembly and second assembly are proximate one another and form a thermal processing chamber,

a thermal transfer unit disposed in the second assembly, the thermal transfer unit having a workpiece support surface that is heated and cooled in a controlled manner, the one or more elements of the first or second assemblies bringing a surface of the microelectronic workpiece into direct physical contact with the workpiece support surface of the thermal transfer unit as the first assembly and second assembly are driven to the thermal processing position by the actuator.

25. An apparatus for thermally processing a microelectronic workpiece, the apparatus comprising:

chamber means for forming a thermal reactor chamber comprising at least first and second chamber members that are movable relative to one another;

means for providing relative movement between the first and second chamber members between at least a loading position in which the microelectronic workpiece may be loaded or unloaded from the chamber means, and a thermal processing position in which the microelectronic workpiece is thermally processed;

a thermal transfer means disposed in the reactor chamber for heating and cooling the of the microelectronic workpiece.

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